Department of Chemical Engineering

A Life Cycle Assessment on Various Alternative Liquid Fuel Options in Western Australia

Lan Zhen Wang

This thesis is presented for the Degree of

Doctor of Philosophy

of

Curtin University

January 2020

Blank page

DECLARATION

I certify that this thesis contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no materials previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of Curtin University. I give consent to this copy of my thesis when deposited in the Curtin University Library, being made available for loan and photocopying.

Date: 06 January 2020

ACKNOWLEDGEMENT

I would first like to thank my thesis advisor Prof. Hongwei Wu for his vital role in providing technical support and guidance throughout this study. The completion of this study is not possible without his help during my post-graduate study. He consistently encouraged me to think creatively and steered me in the right direction whenever he thought I needed it.

Second, I would also like to acknowledge Dr Yun Yu and Dr Xiangpeng Gao for their help. Their acquaintance and support for me are gratefully acknowledged.

I would like to thank Professor Richard James Harper and Dr Stanley John Sochacki for discussing Phase Farming of Tress with me and directing me to standard practices.

Finally, I must express my very profound gratitude to my mum, Mrs Meizhi Sun, my deceased father, Mr Youde Wang, my sisters, Mrs Judy Dooley, Mrs Xiaozhen Wang and my brother Mr Wei Wang for providing me with unfailing support. I would also like to thank my husband Brendan Rellis and my daughter Xi Ella Wang for continuous moral encouragement and financial support throughout the process of researching and writing this thesis.

Author

Lan Zhen Wang

EXECUTIVE SUMMARY

Renewable energy is an emerging form of energy collected from renewable resources that can be constantly replenished on a human timescale. Over the past decades, renewable energy has gained extensive attention in the world. Many researchers agree that conventional fossil fuel can be replaced by renewable fuels which will result in the substantial reduction in greenhouse gas emissions. Australia faces particular challenges in this aspect because of its unique geological characteristics and a small but widely dispersed population. Liquid fuel productions from Australia's economic crude oil reserves have been estimated to last for another approximately 25 years, and gas reserves will last for 150 years. Therefore, the Australian energy intensive industries are urgently seeking renewable fuels as priority for future energy security.

In Western Australia, there has been an increasing interest in substitution of fossil fuels by biofuels derived from wastes, starch, biomass and microalgae. These biofuels offer several potential advantages, including recycling the wastes, management of dryland salinity and utilising carbon dioxide from plants. However there are some challenges that still hinder the biofuel industry. These include, (a) undesired by-products such as glycerol from biodiesel development have impeded the biodiesel development; (b) insufficient water supply for biomass production is also a challenge due to the unique meteorology in Western Australia; and (c) land-use change is another environmental concern.

Extensive research and assessment efforts have been made previously in biofuels production. For example, crude bio-oil was obtained from mallee biomass via the fast pyrolysis process. In addition, the microalga biodiesel process was examined whereby glycerol combined with bio-oil and biochar to form the slurry. Nevertheless, comprehensive life cycle assessments (LCA) are still needed for evaluating the environmental sustainability of biofuel production processes.

The main objective of this study was to assess the energy, water and carbon footprints of biofuels production processes and the land-use change and by-product utilisation.

The biofuel production processes focus on three specific biofuels: (a) biomass from phase farm with trees; (b) biodiesel from waste cooking oil with utilising the by-product (crude glycerol); and (c) bioslurry from biochar bio-oil and crude glycerol. The main research outcomes of this study are summarised below.

Firstly, this study investigates the life cycle energy and carbon footprints of biomass produced with short reforestation phases in a dryland (367 mm/yr annual rainfall) farming system in Western Australia. The results demonstrated that the base-case energy footprint of biomass production is 25 kJ/MJ biomass, and the carbon footprint 3.05 g CO_2-e/MJ biomass, with the majority of both contributed by biomass harvesting and transportation. The energy and carbon footprints are sensitive to biomass productivity (1.8 – 6.7 dry t/ha/year), and are in the range of 14 to 52 kJ/MJ biomass and 6.32 to 1.72 g CO_2-e/MJ biomass, respectively. The range in energy footprint values is slightly wider than those from biomass from a conventional alley farming system (14 – 35 kJ/MJ biomass). The range of carbon footprints is slightly narrower than the alley farming system (-14.5 to 3.1 g CO_2-e/MJ biomass). Both energy and carbon footprints vary with species used, planting density and location within the landscape, and this variation suggests that the efficiency of this system can be further improved through manipulation of these factors. The water footprint was high at upper slopes with lower stem density but it was low at lower slopes with higher stem density. The low GHG emissions of agricultural process and carbon sequestration in reforest process have encouraged agro-forestry as a future farm system to improve the salinity and land erosion issues whilst providing a stable feedstock as renewable fuel.

Secondly, the overall life cycle energy water and carbon footprint are analysed based on biodiesel from the waste cooking oil process that involves by-product (crude glycerol) utilisation, transport efficiency and bio-refinery plant location selection. The by-product from biodiesel (glycerol) is blended with bio-oil from biomass and methanol to form a new fuel, namely the BMG blend. This blend comprises bio-oil, glycerol and methanol in 70, 20 and 10 wt% respectively. Parallel to the PFT biomass process, the life cycle of biodiesel from WCO was also assessed. Overall the total energy consumption and the greenhouse gas (GHG) emissions of the entire biodiesel-BMG process were 160.3 kJ/MJ biodiesel and 55.7 g CO_2-e/MJ biodiesel respectively. The overall energy ratio was 1.14. The carbon sequestration from land-use and land-use change was -0.01 g CO_2-e/MJ biodiesel. The biodiesel production cost is halved after taking the BMG value into consideration.

Finally, a bioslurry fuel was considered in this study. This BGB slurry was the mixture of bio-oil, crude glycerol and biochar in 60, 22 and 18 wt% respectively. The BGB slurry did not require heavy-duty pumps due to its thixotropic behaviour, low solid concentration (< 20 wt%) and particle sizes less than 70 µm. The overall carbon and energy footprints of the biodiesel-BGB slurry process were similar to the biodiesel-BMG blend process. The energy and carbon footprints of the biodiesel-BGB slurry process were 154.4 kJ/MJ biodiesel and 74.1 g CO_2-e/MJ biodiesel respectively. Both processes were economic sustainable. The biodiesel-BMG blend process required 0.5% less capital than the biodiesel-BGB slurry. The biodiesel-BMG blend process could have gained $0.38/kg of BMG blend, and the biodiesel-BGB slurry process has gained $0.40/kg of BGB slurry. Nevertheless, the biodiesel-BMG blend process sequestrated more carbon than biodiesel-BGB slurry process due to excess biochar was applied as fertiliser. Such findings have shed lights to this new promising process, thus indicating that utilising the crude glycerol biodiesel production process is close to becoming a commercial reality.

The findings from this study serve to (a) encourage the domain refinery businesses to improve the utilisation of crude by-products (b) encourage further search of the different biofuels options, and (c) the agro-forestry is recommended as a future farm system to improve the salinity and land erosion issues whilst stabilising the biomass feedstock for renewable fuel processes.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1 Introduction

Renewable energy is receiving increased attention as an alternative fuel source to fossil fuels not seen in previous decades as the fossil energy is rapidly depleting and it is now near the end of its life. Hence, it is inevitable that the world must go through an energy transition towards clean energy. It is clear that with successful effective policies to provide investment certainty, the clean energy transition will get underway throughout the world. Some literature has shown that the majority of world energy investment is being invested in renewable energy and efficiency solutions because this benefits the community, economy and environment. According to the research, at current rate of consumption, earth has 53 years of oil (Csmonitor, 2014), 40 years of gas and 70 years of coal reserves left. (MAHB, 2019).

Australian energy resources are a source of considerable prosperity for all Australians. The sustainable, low cost, and reliable energy support the competitiveness of significant parts of Australian industrial base. Unfortunately, the fossil energy resource is a finite source, i.e., the crude oil reservoir will be emptied in near future according to current productivity (Australian Bureau of Statistics, 2016). Creating feasible clean energy products and services are the current major challenges for the sustainable energy transformation stage in Australia (AEMO, 2013).

In 2017-18 Australia consumed 6172 petajoules (PJ) energy while the energy production was 18603 PJ. Of these, 17% of the total energy production is renewable energy (Department of the Environment and Energy, 2019), but the majority of the energy comes from fossil energy. Australia has rich fossil fuel and renewable energy resource that include the world's largest uranium resources. On the other hand, Australia has some of the highest per capita greenhouse gas (GHG) emissions in the world. Australia outperformed its Kyoto Protocol targets due to the spread of a small population across vast distances, thus resulting in large emissions from both transport and electricity generation. Greenhouse gas emissions from different sources, such as energy and industrial processes, agriculture and waste are relatively stable but emissions from land-use and land-use change forest (LULUC) decreased by 93.9% and waste decreased by 35.7% at the end of 2013 (Shahiduzzaman & Layton, 2015).

Australia's 2030 target is to reduce greenhouse gas emissions to 26-28% below the 2005 level. In order to achieve significant emission reductions the government has implemented a suite of Direct Action policies, which include the 20 million trees programme and 23 per cent of Australian electricity from renewable energy by 2020 (Australian Government - Department of the Environment, 2015). Considering the high GHG emissions per capita and depletion of fossil fuel reserves in Australia, recycling the energy waste and efficient production of renewable energy can provide a significant balanced distribution of feasibility and sustainability in Australian renewable energy transform stage.

1.1 Transformation of renewable energy supply in Australia

Australia has the world largest known economic uranium resources, the fourth largest coal (black and brown) resources and substantial conventional and unconventional gas resources (Geoscience Australia, 2019). As at December 2014, the total economic demonstrated resources and the total demonstrated resources were 3,519,155 and 6,277,275 PJ respectively (Geoscience Australia, 2019). Australia has probably the most favourable global physical conditions for reliance on renewable energy sources. For example, Australia has some of the best wind resources in the world, significant hot rock geothermal resources, good opportunities to exploit the ocean energy resource and vast potential source of solar energy. The total renewable energy sources have grown strongly, from at only 2% of total energy supply in 2014 (Australian Bureau of Statistics, 2016), then 14% of Australia's electricity generation in 2014-15 (Geoscience Australia, 2019), and increased to approximately 16% in 2016 (Department of the Environment and Energy, 2017b), now it is about 19% of total electricity generation in 2018 (Department of the Environment and Energy, 2019). Although the development of the renewable resources is remarkable, they are still not yet readily comparable to non-renewable at a site.

It is clear that Australia's future energy security is needed while reducing greenhouse gas emissions from fossil fuels to meet the Australia 2030 Target. So far Australia has adopted 17% renewable energy since the 1950s (Department of the Environment and Energy, 2019). The difficulties of transforming fossil energy to renewable energy supply are technical, political, financial, social and cultural issues (Effendi & Courvisanos, 2012). Recognising the balance of feasibility and sustainability of renewable energy is the first path to successfully overcome those hurdles.

1.2 Biofuel commercialization in Australia

Biofuel is still an infant industry in the world; there are still a lot of barriers for the commercialization of biofuels in Australia. In 2003, David Lewis has reported on the feasibility of Microalgae Biofuel commercialisation based on the Muradel demonstration facility in Whyalla, South Australia. The Muradel biofuel project has demonstrated that green crude renewable diesel from microalgae had a positive energy balance and smaller carbon footprint than conventional diesel, but the economic forecast for commercial production is unfavourable unless the feed price is greatly reduced from $400 per dry tonne biomass or the technology is significantly improved. The author also found that the fall in the crude oil price in 2014 raised the risks for financing a crude biofuel production project in the short term. Nevertheless, a biofuel production project is financially feasible if (a) the productivity is maximised (b) the production costs could be reduced by 44%, and (c) cheaper variety feed options are available (Lewis, 2015).

1.3 Western Australian situation

Western Australia consumed 1206.6 PJ energy in 2017-18 mainly by mining sector, manufacturing and electricity generation, and less than 2% energy was from renewables (Department of the Environment and Energy, 2019). Among all the renewable energy, landfill and biomass occupy less than 5% of the total renewable energy (Climate Council, 2014). Western Australia has significant forestry and agricultural industries with some agricultural areas severely affected by salinity. There are potential green energy resources that grow in the salinity areas to improve the scald soil quality whilst the tree biomass is harvested for pyrolysis refinery, but most of these energy resources currently have no commercial use.

Western Australia has few potential feedstocks that are suitable for bioenergy production. Firstly, Western Australia generates 45ML of waste cooking oil annually, so recycling waste cooking oil from metropolitan areas to produce biodiesel. Secondly, the native plants from salinity land management are potential feedstock for bio-oil refinery. Traditionally Mallee was harvested for making fences and extracting essential oil with lots of green wastes ending up in landfills (Penfold & Willis, 1954). However, the rich essential oil contents in Mallee have encouraged chemists and engineers to pyrolyze mallee wastes or mallee trees into bio-oil. This potential bioenergy is not only environmentally friendly, it also reduces GHG emissions. Thus biodiesel and bio-oil feedstocks such as waste cooking oil and biomass have received much attention as alternative fuels.

1.4 Objectives of this thesis

The main objective of this study was to determine the carbon and energy footprints of biofuel production in Western Australia by conducting the Life Cycle Assessment under typical Western Australia landscape and metropolitan layout parameters. The biofuel productions are mainly focused on biodiesel from waste cooking oil and bio-oil from biomass in Western Australia. However, this study also considered (a) utilising the by-product (crude glycerol) by blending with bio-oil and methanol to form a new fuel, namely the BMG blend, and (b) mixing biochar, bio-oil and crude glycerol to form BGB slurry. The feasibilities of traditional and new processes were examined by analysing the production costs through evaluating the land, water, and labour requirements of a large-scale biofuel production.

A comprehensive literature review on the energy and carbon footprints of energy fuel options was conducted and discussed in Chapter 2, followed by a methodology in Chapter 3, in which the methods of accounting the energy requirements and energy outputs of the overall bio-refinery plant location and the process, and also the carbon and water footprint assessments are described. The results of the economic feasibility of the new biodiesel-BMG blend processes were discussed in the subsequent Chapters 5, the discussions of the biodiesel-BGB slurry process were in Chapter 6. The conclusions were derived from the assessments of footprints and commercial viability. These and recommendations for future work are then summarised in Chapter 7.

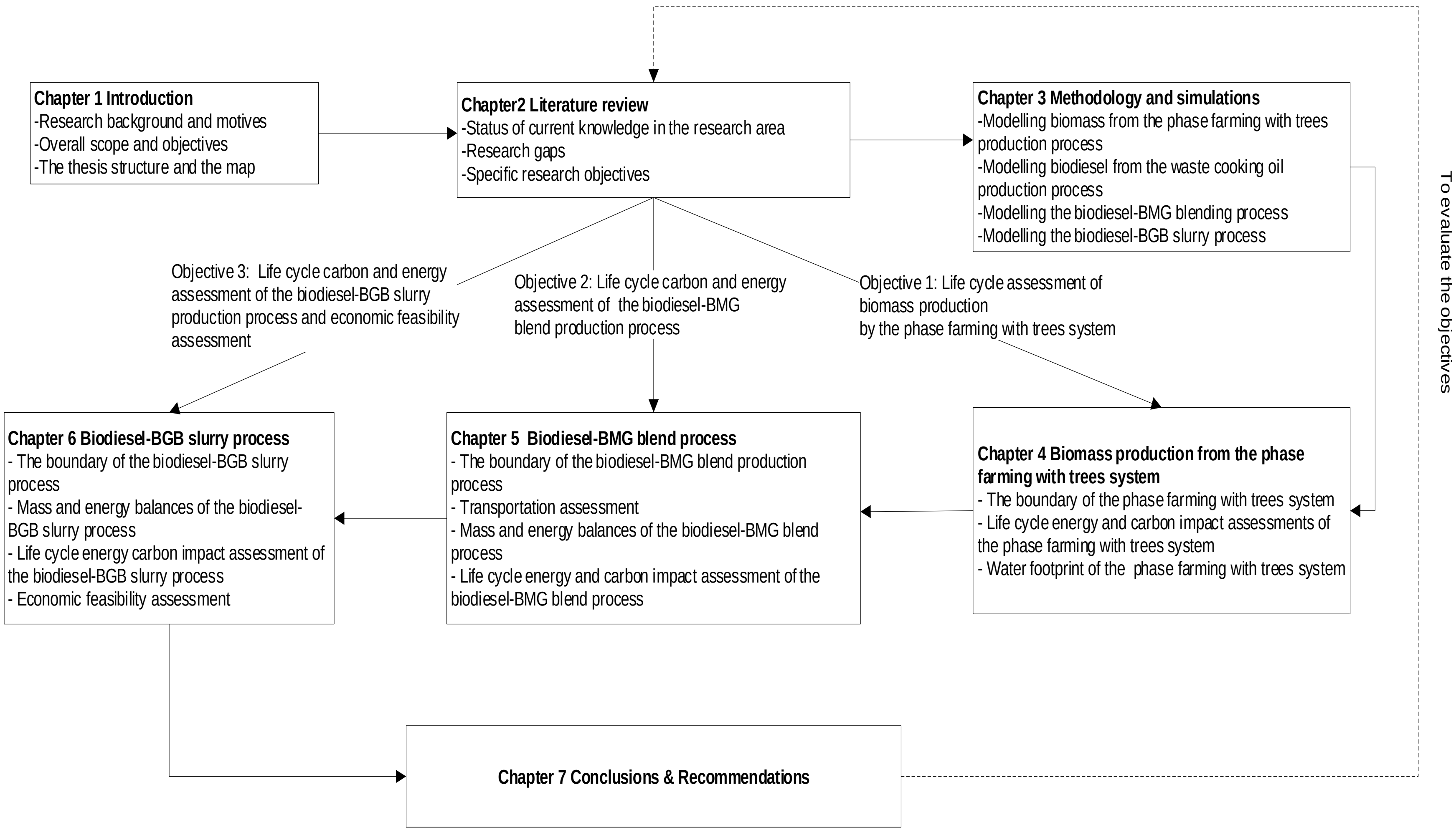

Figure 1-1: Thesis map

Chapter 2 Literature Review

The energy and carbon footprints among the different fuel options under unique Western Australia geological conditions are described in this chapter. In the past decades, it has been extensively studied not only on biofuels from varieties of feeds and also utilising the by-products for the developing of clean and sustainable energy and fuel technologies (X. Gao, Yu, & Wu, 2013; Wu, Fu, Giles, & Bartle, 2008; Yu, Bartle, Li, & Wu, 2009; Yu, Bartle, Mendham, & Wu, 2015; M. Zhang & Wu, 2014). The majority of biofuels proposed are biodiesel obtained from vegetable oils and fats, biodiesel from microalgae, and bio-oil from biomass pyrolysis process. Biodiesel is technically more mature than bio-oil, where a few pilot biodiesel plants have been successfully run, but a lot of improvement is still required such as utilising the abundant by-product crude glycerol (Biodiesel Magazine, 2016; Bioenergy Australia, 2016).

Bio-oil has even been researched in the past decades, but the knowledge of the biofuels are still challenging due to its complexity. The diverse array of these research activities includes advanced analytical chemistry, development of kinetic models, computational fluid dynamic studies, the design of new reactors, environmental assessment and economic analysis (Sharifzadeh, Wang, & Shah, 2015). Mettler et al. have identified ten fundamental research challenges to overcome the bio-oil commercialising hurdle. (Mettler, Vlachos, & Dauenhauer, 2012). They emphasized on understanding the chemistry mechanism but others lead attention to economic and technical assessments (Papanikolaou et al., 2008; M. M. Wright, Satrio, Brown, Daugaard, & Hsu, 2010; Wu et al., 2008; Yu et al., 2009; Yu & Wu, 2010). Nevertheless, these biofuel refineries are still an infant in the fuel industry. This chapter is concludes by summarising the findings of the previous studies and identifying the objectives of this current study on optimization of the energy fuel options under particular Western Australian geological condition.

2.1 Biofuel processes overview

Biofuels are an alternative fuels that can be applied in transport sector as well as stationary fuel engines. During last decades, most researchers focus the biofuels that are produced from cellulosic materials. These raw materials are considered as sustainable if they result in high yields of production and low GHG emissions but require less energy input and agricultural land-use.

In Australia, agricultural land holdings constitute less than half of Australian land mass (Australia Bureau of Statistics, 2011) and almost half of Australian land is arable land or desert. In past of decades, agroforestry salinity control management was thoroughly studied by number of institutions and researchers (Wu et al., 2008; Yu et al., 2009). Moreover, reforest abandoned salinized farmland was studied and recommended reforest native high salt tolerance native trees would be another option of potential solutions (Marcar & Crawford, 2004; Sochacki, Harper, & Smettem, 2012). Planting deep root trees seldom sufficient to overcome salinity problems but it is part of the salinity management, and it is important part of a comprehensive approach. For example, planting large amount trees around catchment area will help controls. Thereafter, commercial farm forestry increasingly catches rural business attention. The interest generated by land owners, farmers and government programs. Based on those issues and restrains, producing biofuels with zero GHG emissions and less or zero agricultural land requirement is a challenge of the biofuels production development.

Under Australian agricultural land restrains, various biofuel processes of utilising sustainable feedstocks have been developed, such as biodiesel from algae process, biodiesel from domestic waste oil and tallow process (Beer, Grant, & Campbell, 2007; Bioenergy Australia, 2016; Scott, 2013), ethanol from agricultural residues process (Gifford, 1984) and bio-oil from forestry resources process (AgriFutures Australia, 2014; S.Mani, Sokhansanj, X.Bi, & A.Turhollow, 2006; Yu et al., 2009). Previous studies mainly focused on the biofuel processes only but the environmental sustainability requires the understanding of water resources and land-use change association. This section reviews the Australian land water conditions and by-products utilisation that are associated with biofuel processes.

2.1.1 Biomass from native plants in salinity land in Australia

2.1.1.1 Salinity issue and current forestry condition

Since the 1850s, large numbers of Europeans settled in Australia mainly due to the discovery of gold, More than 100 million hectares (ha) of native forest and woodland have been cleared and used for agriculture, mining and city establishment (Australian Bureau of Statistics, 2002). However, agricultural production has led to increasing levels of soil salinity. In Australia, increasing salinity is a significant environmental problem. The National Land Water Resources Audit estimates that 5.7 million hectares have a high potential for the development of dryland salinity, and predicts this to rise to 17 million hectares by 2050 (Hamblin & Derrick, 2001).

Since 1998, the United Nations Framework Convention request Land Use and Land-Use Change (LULUC) report should be considered in all relevant articles, such as environmental reports, journals, etc (Penman et al., 2003b; Watson et al., 2016; Weiss et al., 2015) . Up to 2013, Australia has 149.4 Mha of the forests; it comprises 147.4 Mha of native forests and 2 Mha of plantations as shown in Figure 2-1. Data from the Australian National Greenhouse Accounts: National Inventory Report 2010 Volume 3 estimated the total afforestation and reforestation area for the current inventory year was 1.122 Mha, Volume 2 of the report estimated the CO_2-e net emission in 2010 in Land converted to forest land sector was negative 17.258 Mt (Department of Climate Change and Energy Efficiency, 2012). Hence in LULUF-afforestation and reforestation section, GHG net emissions were negative 15.3815 t CO_2-e per ha per year in 2010. The March Quarterly Update of Australia's National Greenhouse Gas Inventory reported the annual net CO_2-e emissions were 567.5 Mt CO_2-e, where LULUCF-afforestation and reforestation section was negative 20.9 Mt CO_2-e per year (Department of the Environment, 2017). The emission trend is slightly decreased as the results of more reforestation activities being done during 2010-2013.

The Western Australia land is under severe salinity threat. In 2002, Western Australia Statistical indicators showed that the most salinity land affected in Australia was Western Australia. Somewhere between 1.04 to 1.2 million hectares of agriculture, and almost 2 million hectares of agricultural land across Australia (Australia Bureau of Statistics, 2010; Mayer, Ruprecht, & Bari, 2005).

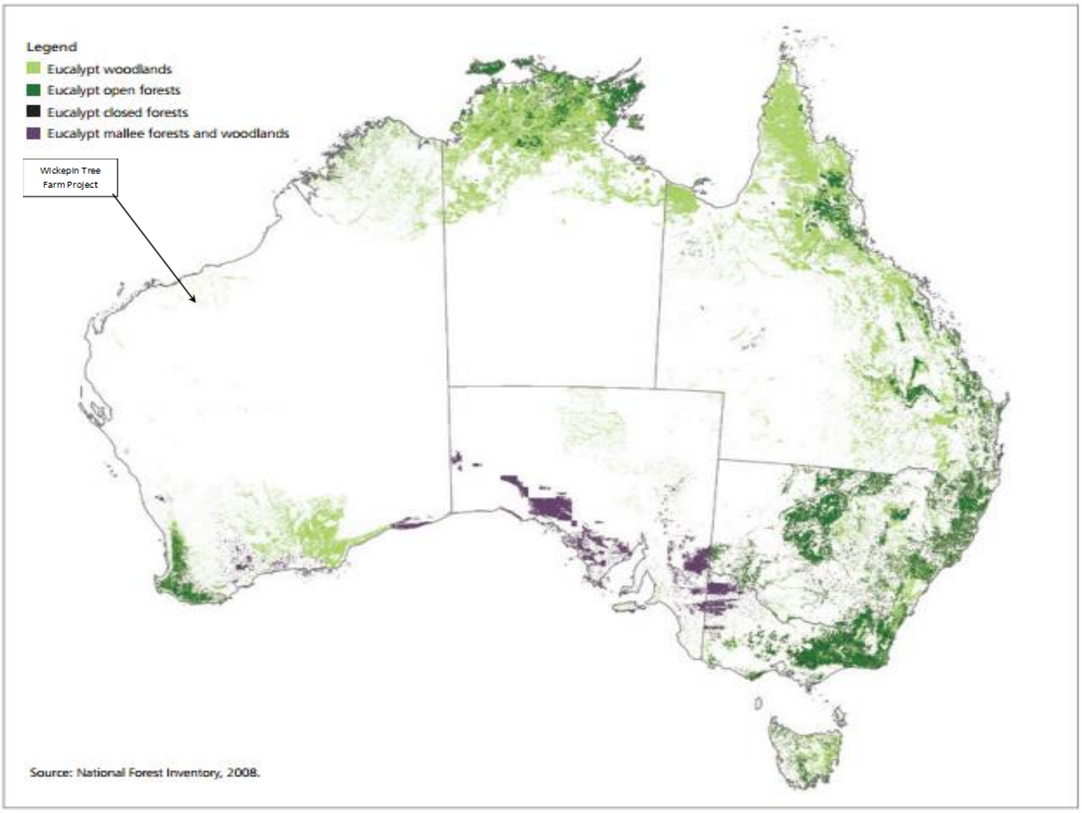

Figure 2-1: Eucalypt Forest distributions (source: National Forest Inventory 2008)

Primary salinity develops mainly in areas where rainfall is insufficient to leach salts from the soil profile and evaporation is high. There is about 29 million hectares in Australia – 14 million hectares of salt marshes, salt lakes and salt flats and 15 million hectares of naturally saline subsoils (Department of Agriculture and Food, 2019). The quantity of the reforest salinities land area and annual rainfalls were determined in order to quantify the biomass productivity as shown in Table 2-1. Salinity affects more than 1 million hectares in the south-west of Western Australia (Department of Agriculture and Food, 2019). The National Land Water Resources Audit predicts that the dryland salinity would be tripled by 2050 (Hamblin & Derrick, 2001). The Australian states and territory governments have established the National Action Plan for Salinity and Water Quality (NAP) and identified high salinity risk regions throughout Australia as shown in Figure 2-2. By accessing various government data, the total area was 0.557 million hectors which could be used for planting native trees if 100% of the severely scald land was reforested to reverse the issue of salinity. More recent research reviews the development of salinity in the agricultural areas (Read, 1988).

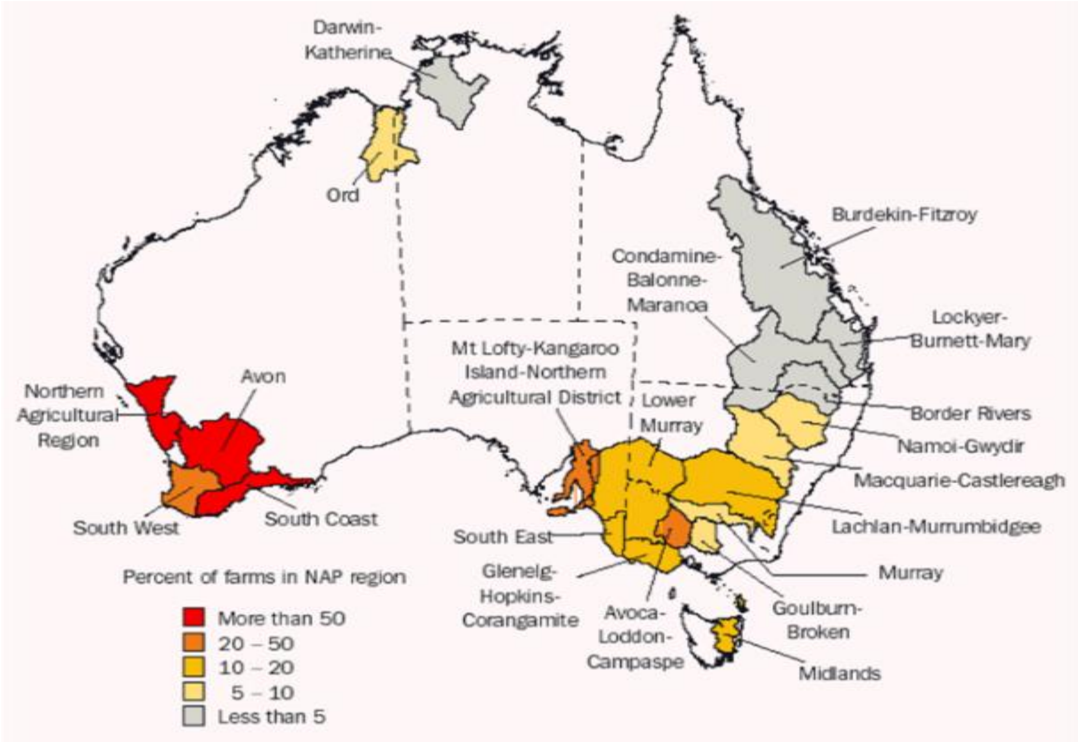

Figure 2-2: NAP regions, proportion of farms affected by salinity – 2002 (Australian Bureau of Statistics, 2002)

The salinity is caused by extensive land clearing and farming irrigation activities. There is no quick way to fix the salinity problem. This can only be prevented and reduced by carefully designed and monitored managements. In 2003, salinity management practices in Western Australia have planted 63.2% of Avon NAP region with trees and 42.8% of earthworks constructed, that included levees, banks and drains (Australian Bureau of Statistics, 2002). Engineering options such as drainage, pumping and water diversion for managing salinity is also taking place after the salinity problem has been issued nationally (Shaw, Gordon, & Witney, 2011). The highly salted abandoned farmlands were suggested to be reforested with the aim of producing biomass fuel (Sochacki et al., 2012). The salinity management was conducted by S. Cleary in 2009. His recommendation was to fully plant deep-rooted salt-tolerated trees in high and moderate salitised land. He also suggested 50 percent of low salt affected land be planted with deep-rooted trees (Cleary, Bari, & Smettem, 2009). Also, some strategies have been advocated to increase the soil quality and water depletion, such as tree belts configuration or phase farm with trees system (Richard J. Harper, Sochacki, Smettem, & Robinson, 2014; Wu et al., 2008).

Table 2-1: Salinity land areas and mean annual rainfalls in WA.

	Salinity land Area (ha) [a]	**Mean Annual Rainfall range (mm)** [b]
South West	3090	400-1200
Central	91974	300-400
Great Southern	62532	300-600
South Coast	9217	400-800
Northern Agricultural region	86400	300-600
Total	253213	

[a] Data were adapted from Department of Agriculture and Food (Department of Agricuture and Food, 2016)

[b] Data were adapted from Bureau of Meteorology (Bureau of Meteorology, 2014b)

2.1.1.2 Valley system and phase farming with trees system in Western Australia

Recently the abandoned reforest salinized farmland was studied and the authors recommended that reforest native high salt-tolerance native trees would be another option of potential solutions (Penman et al., 2003a; Watson et al., 2016; Weiss et al., 2015). The Australian government has encouraged many research institutions to seek solutions. In addition, the government has engaged the local farmers to cooperate with research groups.

The tree belts strategy has been developed in Wheatbelt areas with wide-spaced narrow belt configurations integrated with existing agricultural activities since the 1990s (Yu et al., 2015), where this is also named as the tree valley system. Yu et al. have studied the tree valley system over 12,000 ha through different sites since the activities were carried out (Yu et al., 2015). They have studied in depth the carbon and energy footprints when the mallee is used as feedstock for bio-oil from biomass process. Yu and co-workers concluded that low carbon footprint is achievable even if the soil is unfertilised, although the fertilising needs to be considered in the life cycle analysis.

Table 2-2: Benchmarking of life cycle energy and carbon footprints with biomass productions from different systems

Authors	Country region	Agricultural system	Energy footprint (kJ/MJ biomass)	Carbon footprint (gCO_2-e/MJ biomass)	Notes
(Wu et al., 2008)	Western Australia	Narrow valleys between agricultural crops	34.8	NA	50 production years with initial 5 years to first harvest followed by 15 coppice harvest cycle.
(Yu et al., 2015)	Western Australia	Narrow valleys between agricultural crops	14.3 - 21.6	-14.5[a], 3.1[b]	67 production years, aboveground biomass considered.
(F. Zhang, Johnson, & Wang, 2015)	USA	Forest activity	10.86	1.08	Excluded all indirect inputs
(Sonne, 2006)	Western America	Forest activity	NA	2.66	50 years rotation age, considered direct and indirect inputs
(González-García, Berg, Feijoo, & Moreira, 2009)	Sweden, Spain	Forest activity	24.35	NA	All forest operations from site preparation to pulp mill gate, excluded seedling and machinery production.
(Dias et al., 2017)	Canada	Narrow valleys between agricultural crops	3.27	0.33	Willow grew after crops, 19 years production period with initial 5 years to 3 years harvesting cycle.
(Valente, Spinelli, Hillring, & Solberg, 2014)	Norway, Italy	Forest activity	1.22	17.17	The deep root trees grew at different location, considered all direct and indirect inputs

a Considering carbon sequestrations because of below-ground biomass and land-use change.(Yu et al., 2015)

[b] Without considering the carbon sequestrations because of below-ground biomass and land-use change.(Yu et al., 2015)

Nevertheless, the disadvantage of tree belts is displacement of food production in water-limited environment and also competition between the trees and adjacent crops due to the large tree roots area. This will obviously depend on the nature of the local hydrological and geological system (Richard J. Harper et al., 2014).

Planting deep root trees with narrow belt configuration seldom is sufficient to overcome salinity problems because this will obviously depend on the nature of the local hydrological and geological system. Harper et al. have proposed the phase farming of trees system (PFT) that plant native trees in scald land for four years and then plant crops for ten years (Richard J. Harper et al., 2014; Sochacki et al., 2012). Table 2-2 has presented the comparison of other published literature.

This experiment had been studied and developed with wide range possibilities for management, including high planting densities, or use of species which would not have been considered otherwise in a particular environment (Richard J. Harper et al., 2014). This PFT revegetation experiment has been performed successfully to improve salinized farmland and control the soil degradation. Harper et al. also examined the soil water deficiency at the tree phase and concluded that the soil condition had improved and suited agriculture for further soil condition improvement (Richard J. Harper et al., 2014). So far, no many life cycle assessments have been considered by the researchers in the PFT experiment previously, thus the life cycle assessments were conducted in this study.

2.1.2 Bio-oil pyrolysis process from biomass

The pyrolysis of bio-oil from biomass concept was established and the technology has matured since. Large scale pyrolysis processes have been developed, simulated and studied in recent decades. Three primary routes were obtained for converting biomass into liquid fuels. The first route was syngas production by gasification, the second was bio-oil production by pyrolysis or liquefaction, and the third route was hydrolysis of biomass to produce the sugar monomer unit. In order to produce the bio-oil fuel, liquefaction of biomass by fast pyrolysis with further pyrolysis oil upgrading is a recommended method (Sullivan, Boduszynski, & Fetzer, 1989). However, crude pyrolysised bio-oil has some common features that differs from the fossil crude oil, and the chemical composition varies significantly depending on the feedstock composition, the process condition and the post-treatment (M. Zhang, 2015b). Therefore hydrotreating and hydrocracking processes maybe have advantages to improve the bio-oil process that use hydrogen to remove impurities and break large molecules down into smaller ones. Nevertheless, economic and environmental assessments should be taken place to investigate the feasibility of the process (Bhran, Shoaib, & Umana, 2016; Noguera et al., 2012; Tiwari et al., 2011).

Technically, upgrading bio-oil is expensive because the instability of the bio-oil and enormous chemical compounds in the bio-oil, purifying bio-oil will be too costly to be feasible. Hence, blending bio-oil with other fuels to form new fuel has gained attentions. This blending fuel will be more attractive if it can be used directly in particular devises or equipment (Krutof & Hawboldt, 2016). Mingming Zhang has successfully invented a stable fuel mixture of bio-oil, glycerol and methanol to avoid upgrading of crude bio-oil and glycerol process (M. Zhang, 2015b). Soo-Young No has investigated the properties of bio-oil/oxygenated fuel (ethanol, diglyme) on the spray and combustion characteristics and recommended bio-oil blends are reducing in soot emission but corrosive for engine nozzles (No, 2014). Yang et al. have reviewed the recent developments in techniques on bio-oil stability and concluded that solvents addition and emulsification had effectively increased bio-oil stability (Yang, Kumar, & Huhnke, 2015). Nevertheless, there is no economic assessment available in the literature, and feasibility analysis is highly attractive from researchers to develop a new process for emulsion blends biofuel, which is also within the scope of this study.

2.1.3 Energy footprint of bio-oil production

Life cycle energy assessment is an important method to evaluate the energy and environmental impacts of various biofuels. An important energy footprint parameter is energy ratio. This ratio is the ratio between energy outputs and inputs which were counted directly and indirectly (Wu et al., 2008). Direct energy requirements are counted from fuels, electricity and heat from the process. Indirect energy requirements are accumulated from materials, chemicals, farm implements, vehicles, processing equipment and labour.

2.1.3.1 Biomass production energy input and ratio

According to Pimentel et al., producing large scale biofuel from food crops is not an option for replacing fossil fuel because of land and water competition and food security. These are among the social and environment negative impacts. The authors suggested that the future biofuel productions should be linked to other agro-industrial activities at an appropriate scale. The properly managed and minimized energy consumed agriculture could be an interesting option for the future acceptable biofuels (Pimentel & Burgess, 2014). According to the analysis of Ferry et al. the primary energy requirements during crop growing were 12111.93 MJ/ha in Western Australia. The net energy ratio for growing rapeseed to biodiesel refinery was 0.97-1.72, and better utilisation of by-products could lead to higher energy ratio (Rustandi & Wu, 2010). In Western Australia, some literatures have provided detailed life cycle analysis for Mallee plantation. Yu et al. have determined that the energy footprint from mallee biomass was 299-451 MJ/dry tonne biomass, the energy varies due to soil condition (Yu et al., 2015). In bioslurry case study, Yu et al. determined the total energy footprint of biomass supply chain as 26.4 MJ/GJ biomass if the biomass productivity as 60 green tonne per hectare per harvest cycle (Yu & Wu, 2010).

Most of the energy input calculations in farm productions were agreed except the fertiliser usage. Wu et al. applied the fertiliser at the sappling and coppice stage but no fertilising application in mallee crop establishment stage (Wu et al., 2008). Yu et al. extensively analysed additional fertilizer application in mallee growth at various sites and they found that fertilizer application accounted for 59-72% of total energy input (Yu et al., 2015). May et al. found that fertiliser use in forestry only makes up 1-2% of total use as a result of the low frequency of application and small land areas compared with agricultural systems. Rates of nitrogen and phosphorus application are only a fraction of those used in intensive crops such as sugarcane (B.May et al., 2009). In addition, fertiliser application in forestry varies depending on the soil properties, weather conditions, pasture, plant species and rotations. For the dry salinity land in Western Australia, most of the researchers have suggested that a “starter” type fertiliser should be used at the rate of 125-250kg/ha at the forestry site establishment (Department of Environment and Climate Change, 2008). For example, diammonium phosphate (18-46-0) is used as fertilising in the sowing stage, that is 2836-5673 MJ/ha energy input from fertilization (Wu et al., 2008). This accounts for 12.5-23.4% of the total energy inputs.

Harper and co-workers have proposed a phased reforestation system, termed Phase Farming with Trees (PFT), under which trees are grown for 3 to 5 years (tree phase) and crops are planted in a subsequent 10-20 year agricultural phase (Harper et al., 2014). This method increased the efficiency of water management while producing biomass. Nevertheless, Harper et al. did not apply any fertiliser in the PFT system. Spencer et al examined biomass growth through 19 different sites and concluded that biomass production is more influenced by climatic and edaphic factors, such as the combination of rainfall, evaporation and soil depth. He also mentioned when the impacts of pH and salinity of soil on yield were negative, while soil nutrient has positive effects (Spencer et al., 2019)

2.1.3.2 Bio-oil pyrolysis process energy input and ratio

Developing an energy-efficient biodiesel transesterification process has been researched enormously in the past decades, especially the process of biodiesel from waste oil. There are at least four main biodiesel processes: transesterification, pyrolysis, microemulsion and co-solvent blending. The microemulsion is the hybrid fuel containing TAG in the absence of fossil diesel. Microemulsion and co-solvent blends had gained very little attention due to complicated handling and storage consideration or high cost with solvent, although a few formulas were patented (Dunn, 2010). Pyrolysis or cracking involves the cleavage of chemical bonds to smaller molecules, whereby the process requires high temperature or catalyst. Among those processes, transesterification is the most commonly used method due to high yield, quality and relatively cheap chemical feeds (Dunn, 2010; Sheehan, Camobreco, Duffield, Graboski, & Shapouri, 1998). Some researchers have reviewed the energy output and input of the biodiesel process. It was found that the process energy input does not vary with the type of feed, and the transesterification process energy input is a range of 30.05 to 41.83 MJ/L biodiesel and the energy ratio range from 1.03 to 1.49 (Mohammadshirazi, Akram, Rafiee, & Bagheri Kalhor, 2014; Patil, Gude, Reddy, Muppaneni, & Deng, 2012; Rustandi & Wu, 2010; Sheehan et al., 1998; Singhabhandha, Kurosawa, & Tezuka, 2006).

2.1.4 Carbon footprint of bio-oil production

Afforesting the salinized abandoned farmland can help to mitigate carbon dioxide emission and enrich Australian ecosystem. This endeavour will help to achieve Australia's Kyoto-Protocol annual greenhouse gas target, which is Australia will reduce its greenhouse gas emissions by 25% by 2025, if the world agrees to an ambitious global deal capable of stabilising levels of greenhouse gases in the atmosphere at 450 ppm CO_2-eq or lower (P.Wang, 2000). Currently, large areas of agricultural land in Australia are not used due to increase in salinization, water quality, wind erosion and losses of biodiversity (Harper et al., 2007).

Carbon footprint in agricultural and forestry system has been widely investigated in Australia and the world. This value of carbon footprint can calculated from the total amount of carbon emitted minus the carbon sequestrated from the forest and agriculture. Professor. Takle found that carbon sink created by forests and forest products (9.6 percent) more than offsets the greenhouse gas emissions from agriculture (8.2 percent) in USA (Takle & Hofstrand, 2008). Harris et al. determined that the total GHG emission from agriculture is 3 percent less than forestry activities in the UK, but he also indicated the reduction of emissions from deforestation and agriculture was a significant contribution of GHG emission (Harris & Feriz, 2011).

In Western Australia, Yu et al. calculated GHG emissions were 2.3 kg CO_2-e/GJ biomass of mallee trees and -5.3 kgCO_2-e/GJ include CO_2-e from Land Use and Land Use-Change in Wheatbelt area from a valley farm system (Yu et al., 2015). McGrath et al. estimated that 15 M dt biomass can be produced from the 2.3 M-ha land by short rotation coppicing mallee plantation in Australia (McGrath et al., 2016). According to CSIRO report, if the 5% of total cleared farm land is used for short-rotation mallee production, it would produce 4.3 M dt/yr biomass in WA. Hence the bio-oil productivity was 5.6 green ton / year-ha, CO_2-e emission reduced 40-65% compare to fossil fuel production (McGrath et al., 2016). Farine et al. estimated the production of mallee in Western Australia was 6.5 dt/yr-ha (Farine et al., 2012), with biomass enzymatic fermentation ethanol process, the net GHG emission was 0.2 kg CO_2-e/L (Mandil, 2016). Richard J. Harper developed the PFT system that can produce the mean of 13.8 dt/ha in a 5 years short rotation period in WA (R.J.Harper et al., 2014).

2.1.5 Water footprint

Water footprint was often ignored due to lack of data availability, complexity and high uncertainties, especially the data of underground water (Y.Hoekstra, K.Chapagain, M.Aldaya, & M.Mekonnen, 2011). Water footprint consists of three components: green, blue and grey virtual water. The green virtual water is the rain water precipitation on land that does not run off or recharged the groundwater but is stored in the soil or vegetation. Eventually, this part of precipitation evaporates or transpires through plants. Thus, green water is soil water deficit. The blue virtual water content refers to the surface and ground water that is evaporated from surface water and ground water. The grey water is the volume of water that becomes polluted during production (Network, 2014).

In this study, the water footprint of biomass is defined as the volume of blue water that is used for the biomass in Australia and green water in the soil and the plants (C. Liu, Kroeze, Hoekstra, & Gerbens-Leenes, 2012). In 2006, the World Wide Fund for Nature (WWF) investigated the water footprint in Australia bioethanol and biodiesel.

Table 2-3 shows that Rye to bioethanol has the highest water footprint with 460 m^3/GJ bioethanol, whereas cotton seeds to biodiesel have the lowest water footprint with 4 m^3/GJ biodiesel (Mekonnen & Hoekstra, 2011). The grey water has been analysed by WWF for all the biofuels but it is not considered in this study because the concept is beyond the scope of study.

It is a widely accepted fact that forestry industry prompted higher water footprint. This is a vital factor in Australia due to lack of water supply. Cunningham et al. recommended that reforest or agro-forestry abandoned salinized land is a great way to reform the quality of green and blue water in the dry land at the same time to restore or increase carbon dioxide sinking area (Cunningham et al., 2015). However, Keenan et al. found the changing in land use from agriculture and pastoral lands to reafforestation will significantly reduce water yields and reduce groundwater recharge because the evapotranspiration of forestry land is 200-130 mm greater than agricultural land depends on the rainfall at that location and landscape (Keenan et al., 2004).

Table 2-3: Water footprint of bioethanol and biodiesel for major crops (Mekonnen & Hoekstra, 2011)

Product description (FAOSTAT)	state	Australian Capital Territory	New South Wales	Queensland	South Australia	Tasmania	Victoria	Western Australia	ENTRY-average
Water footprint of ethanol for major crops (m^3/ GJ ethanol)									
Wheat	Green	248	223	202	180	152	157	192	196
Wheat	Blue		4	2	0	15	2	0	2
Wheat	Grey	11	10	12	8	6	8	11	10
Rice, paddy	Green		25						25
Rice, paddy	Blue		113						113
Barley	Green		177	242	153	138	128	164	161
Barley	Grey		16	22	14	12	13	16	15
Maize	Green		50	95			47	117	75
Maize	Blue		78	59			77		67
Maize	Grey		13	13			12	16	13
Rye	Green		539	617	470		401	385	460
Rye	Grey		46	37	60		46	55	51
Sorghum	Green		146	154				119	152
Sorghum	Blue		7	6					7
Sorghum	Grey		10	11				8	11
Potatoes	Green		31	34	12	26	14		17
Potatoes	Blue		27	30	35	24	34		32
Potatoes	Grey		8	7	5	6	5		5
Sugar cane	Green		41	31				23	31
Sugar cane	Blue		3	23				11	23
Sugar cane	Grey		6	7				5	7
Water footprint of biodiesel for major crops (m^3/ GJ biodiesel)									
Soybeans	Green		297	317			249		303
Groundnuts, with shell	Green		165	122					122
Groundnuts, with shell	Blue			53					52
Groundnuts, with shell	Grey		21	17					17
Sunflower seed	Green		545	592			340	416	577
Sunflower seed	Grey		74	73			66	46	73
Rapeseed	Green	197	202		173	194	161	162	180
Rapeseed	Blue								
Rapeseed	Grey	29	37		37	25	32	38	36
Seed cotton	Green		112	126					114
Seed cotton	Blue		254	202					248
Seed cotton	Grey		4	4					4

2.2 Biodiesel from waste cooking oil process

2.2.1 Current situation in waste cooking oil

It is widely agreed that biodiesel is highly biodegradable, has low toxicity and can be directly used in boiler, internal combustion engine. It can also blend with fossil oil to use in current vehicle engines (Beer et al., 2007; Pölczmann, Tóth, Beck, & Hancsók, 2016; Tran et al.). Biodiesel derived from WCO has been widely discussed in different countries, the quantities of the waste cooking oil that generated in different countries were presented in Table 2-4. Numerous studies have examined the environmental and economic feasibility of biodiesel from WCO. For instance, Basheer et al. found that waste cooking oil is a relatively low-cost feed for biodiesel process since the feedstock represents 75-80% of the total production cost. They concluded that 70% of cooking oil could be recovered from restaurants and other resources, thus converting from waste to energy for economically sustainable process (Diya'uddeen, Abdul Aziz, Daud, & Chakrabarti, 2012). Farine et al. reported that 8 million tonnes of waste oil were generated in Australia. The waste oil included canola, animal tallow, waste oil mixture and Pongamia seed (Farine et al., 2012). According to O'Connell, 0.08-0.09 million tonnes of waste cooking oil currently is being collected annually for biodiesel production in Western Australia in 2007 (O'Connell, 2007). The giant mining service company EES provides 200 kt of used cooking oil annually from servicing all mining companies in Australia, most of them in Western Australia.

Disposal of waste cooking oil in landfill is prohibited in Australia but there are no national data on recycling by ABS (Australian Bureau of Statistics, 2006; Queensland EPA, 2013). In 2007, Tom et al. from the CSIRO reported that up to 60-80 kt of waste oil was generated 60-80 kt annually in Australia (Beer et al., 2007). The Australian giant catering company ESS generates 0.176 kt of its used cooking oil every year which is currently being converted into biodiesel by ASHOIL and used in some mining companies for explosion fuel (Spriggs, 2013).

In Western Australia, there are a few recycling companies that collecting waste cooking oil free of charge. In 2006, the BioFuels Taskforce of Western Australia was created and examines different options for encouraging the development of the Western Australian biofuels industry. According to this finding, Western Australia generates 40 kt WCO per year which could be collected and transported to a suitable bio-refinery plant for further recycling into biodiesel production (Dale, 2007). In 2013, the Ashburton Aboriginal Corporation (AAC) recycled in excess of 200 kL used cooking oil from Western Australia's largest mining services company ESS to produce biodiesel which has been successfully used in mining explosion (Scott, 2013). Oil and gas companies have also produced biodiesel and blended it into fossil diesel and use it directly in transport sector.

Table 2-4: Waste cooking oil quantities by countries

Country	Quantity (million tons/year)	Reference
China	13.74	(Liang, Liu, Xu, & Zhang, 2013)
Malaysia	0.5	(Diya'uddeen et al., 2012)
United States	121	(Gallman, 2011)
Taiwan	0.07	(Tran et al.)
Europe	0.7	(Panadare & Rathod, 2015)
Canada	0.135	(Panadare & Rathod, 2015)
Japan	0.45-0.57	(Diya'uddeen et al., 2012)
Ireland	0.153	(Thamsiriroj & Murphy, 2010)
UK	0.22	("Environmental Audit Committee," 2011; Panadare & Rathod, 2015)
Australia	0.08	(O'Connell, 2007)

2.2.2 Biodiesel from waste cooking oil production process

The waste cooking oil is collocated from restaurants, fast food chains and other food industries, and then transported to the bio-refinery undergo the transesterification process. The final product is biodiesel with crude glycerol as the by-product.

The conventional alkali-catalysed process with free fatty acid (FFA) pre-treatment alkali-catalysed process was employed in this study. According to Morais S. and co-workers, the alkali-catalysed process was the most economical process (Morais, et al., 2010). For the traditional biodiesel production process, WCO was collected and transported to the ideal location of the biodiesel plant, mixed with methanol and sulphuric acid to convert FFAs into methyl esters, and then the pre-treated oil can be transesterified with an alkali-catalyst to convert triglycerides into methyl esters. The product biodiesel is then transported to the storage area. This study has adapted the Morais S. data for the traditional biodiesel process simulation.

2.2.3 The current market of crude glycerol

There is a limited demand for glycerine for some feed, beverage, personal care, oral products and pharmaceutical uses. Based on information from the literature, there is an oversupply glycerol from biodiesel production in the market. Creating additional markets for the biodiesel is the current approach to deal with this potential problem.

Historically, high-purity natural glycerine had a fairly stable price of about $1200 to $1800 per tonne in 1970 as well as low-grade glycerol. This stable demand and supply was disrupted since 2003 after biodiesel plants boom. With approximately 1 kg of crude glycerol generated for every 10 kg of biodiesel, the crude glycerol has overflowed the market and has impacted the global glycerol price. The glycerol from biodiesel production has climbed from 0.6 million tonnes in 2006 to 2 million tonnes in 2012 (Ciriminna et al., 2014).

In the past decades, demands of crude glycerol in Asian countries remained weak due to the poor performance of downstream industries like pure glycerol and epichlorhygrin (ECH) (ICIS, 2015). The purification is costly and hence its applications in food, pharmaceutical and personal care products are at high market prices with consistent demands (Rodrigues et al., 2016). The most of biodiesel producers would be under pressure to lower their prices with stocks piling up. (Gan, 2015)

The US glycerine market is facing lengthening supply in 2016 because of oversupply globally (Perez, 2015). According to Ciriminna and co-workers, 2 million tonnes glycerol is expected to reach the market globally every year (Ciriminna et al., 2014). Today, the crude glycerol price is around $600 per tonne and keeps falling. The global glycerol production and prices statistics for 2010, according to Quispe and co-workers, is shown in Figure 2-3 (Quispe, Coronado, & Carvalho Jr, 2013). Thus, converting the crude glycerol to higher value products or adding some value into the glycerol has become an important parameter of economic analysis for bio-refinery plants.

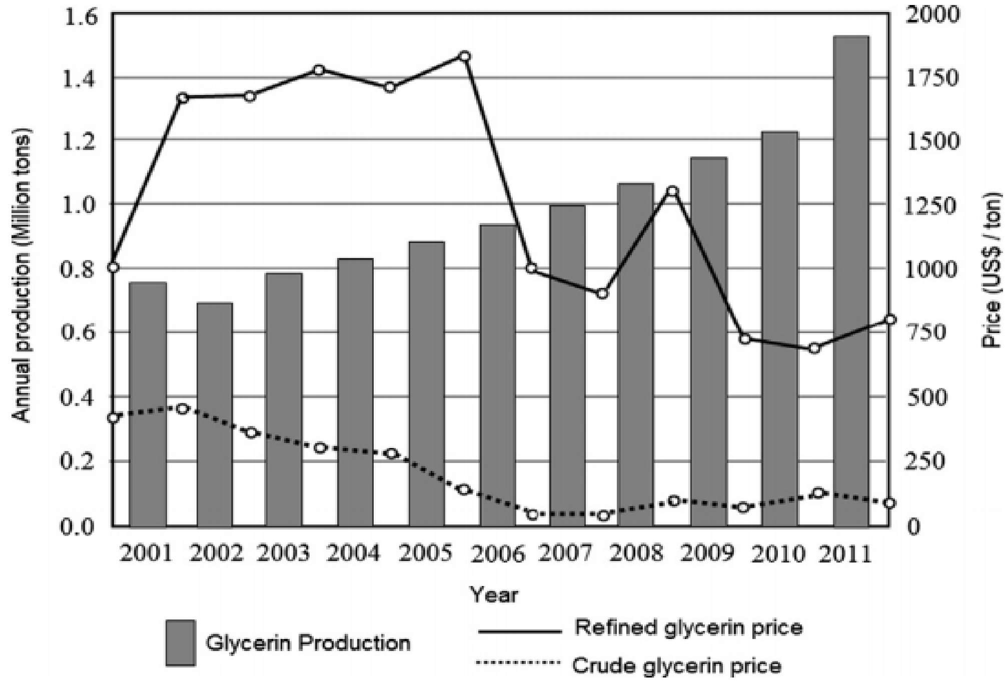

Figure 2-3:Projection of glycerol production and prices (Quispe et al., 2013)

2.2.4 Energy footprint of biodiesel production from waste cooking oil

2.2.4.1 Energy footprint of waste cooking oil collection

Western Australia has a very low dens population (Australian Bureau of Statistics, 2013b). Thus, the energy consumption in transportation is a vital parameter to determine the viability of any preliminary business analysis (Small Business Development Corporation, 2016). The transport sector consumed 1589.2 PJ energy in 2013-14, which is 38% of total energy consumption (Ball et al., 2015). The transport industry is a major user of petroleum products, where it shares approximately 20-21% of total Western Australia energy demand (Australian Bureau of Statistics, 2012a; Govement of Western Australia: Office of Energy, 2011). Among the transport energy consumption, trucks and buses occupy 42.5% of it (Ally, Pryor, & Pigneri, 2015). This data indicates that 89.16 PJ energy is consumed by trucks and buses in Western Australia. In 2014, the Australian vehicles have travelled an estimated 11.3 million kilometres in 12 months. the average rate of fuel consumption for heavy trucks was

56.9L/100 km (Austrlian Bureau of Statistics, 2014). Hence every truck consumed approximately 7.89 GJ/km.

There are a few literature reviews on the impact of WCO collection which mainly focused on the carbon footprint aspect. The findings varied from different regions and countries. For example, Chua et al. showed that the WCO collection stage from the restaurants in Singapore only occupied 1% of the overall biodiesel environmental impact (Chua et al., 2010); similarly, Peiro et al. concluded the impact of WCO collection from restaurants, bars and hotels was very small in Spain (Talens et al., 2010). In contrast, Caldeira et al. have found that the contribution of GHG emission from the WCO collection was between 7 - 50% depending on the collection methods (Caldeira, Queiros, & Freire, 2015). In addition, Jiang et al. concurred with Zhang et al. that WCO was scattered in production points, so a professional recycling logistics system of WCO could be a bottleneck point to improve the biodiesel production (Jiang & Zhang, 2016; Zhang, Wang, & Mortimer, 2012) . In another study, Singhabhandhu et al. found that the WCO collection constituted 0.786% total energy input (Singhabhandha et al., 2006).

Collecting waste cooking oil in Western Australia from restaurants in the metropolitan area has never been examined due to its unique geographic location. Currently, most of the waste cooking oil is collected by the recycling companies, and then sell it to the petroleum companies such as Caltex, Shell or BP to refine biodiesel and blend it into fossil fuel diesel as B20. The price of waste oil is an important parameter to analyse the energy footprint but this information is not currently available therefore, necessary to conduct a literature survey (Beer et al., 2007).

2.2.4.2 Energy footprint of biodiesel from waste cooking oil

Many transesterification processes have been developed from past decades, such as microwave-assisted catalytic transesterification (Teng et al., 2016), sulfuric acid catalyst (Liu et al., 2016) or alkali transesterification (Bradley et al., 2016; Li et al, 2016), supercritical methanol method (Ortiz-Martínez et al., 2016), solid acid catalytic distillation (Gaurav, Ng, & Rempel, 2016), pyrolysis hydrotreating process (David, Winnie, & Claire, 2010) and many more. The energy balance for transesterification biodiesel from the WCO process significantly varies depending on the methods. The total energy input for biodiesel production in the common method is 0.44MJ/MJ biodiesel, transesterification process consumes 0.10MJ/MJ biodiesel and supercritical methanol method requires 0.081 MJ/MJ biodiesel (Biofuel Economy, 2009). According to David and co-workers, the most profitable method was the pyrolysis hydrotreating process (David et al., 2010). This study needs to analyse the bio-oil from biomass process, so it is reasonable to employ the pyrolysis process in bio-refinery. The main focus of this study was determining the WCO collection efficiency and the best bio-refinery location in WA.

Recently, the overall energy footprint has received much attention but the results differ due to logistic and geological differences. Researchers tend to use different parameters to determine the energy footprint of biodiesel from WCO. For example, the overall energy assessment for biodiesel refinery in Singapore was conducted and Celia et al. employed the concept of Life Cycle Energy Efficiency (LCEE) which is the ratio of fuel product energy (FPE) to the total primary energy (TPE). They found that the life cycle energy efficiency of biodiesel from waste cooking oil was 87% which include the waste oil collecting stage in the Singapore case study (Chua et al., 2010).

2.2.5 Carbon Footprint

Unlike the energy footprint, the carbon footprint of biodiesel from waste cooking oil process has been extensively examined by many researchers using different methods and simulators. Thus, it is not a surprise that the results differ significantly depending on the transesterification process and productivity. The Smorgon group from Victoria in Australia reported that GHG emission for biodiesel derived from WCO process was 1.42 g CO_2-e/MJ biodiesel (Smorgon group, n.d.). Similarly, Gaurav et al. developed a new biodiesel process from WCO via solid acid catalytic distillation that resulted in reduction of 16 gCO_2-e/MJ biodiesel assuming the productivity was 4017 kg/hr biodiesel (Gaurav et al. n.d.). However, the main variation of the literature findings is in the collection stage since the biodiesel transesterification process is mature and similar for all systems in the world.

Several assessments of carbon footprint from the WCO collection have been analysed by varier researchers from different countries. Some studies have shown very low carbon footprint at WCO collection. Table 2-5 shows greenhouse gas emissions of the biodiesel process at WCO collection stage and the total emissions among different countries. The GHG emission from WCO collection stage ranges from less than 0.01 to 0.7 gCO_2-e/MJ biodiesel, and the total GHG emissions of the biodiesel processes are 0.9-33 g CO_2-e/MJ biodiesel. It is important to assess the WCO collecting efficiency over the entire biodiesel process. It is also important to know the roll of collecting WCO plays over the whole because of low population vs large areas in Western Australia.

Table 2-5: GHG emissions from Biodiesel WCO process

country	GHG emissions (g CO_2-e /MJ biodiesel)		Reference
	WCO collection	total	
Portugal	0.7	10	(Caldeira et al., 2015)
Span	<0.01	8.1	(Talens Peiró et al., 2010)
Brazil	<0.01	33	(De Pontes Souza, Mendonça, Alves Nunes, & Valle, 2012)
Singapore	0.009	0.9	(Chua et al., 2010)
Japan	0.021	9.16	(Singhabhandha et al., 2006)

The majority of the life cycle assessments of biodiesel process only considered the carbon footprint of transesterification process. Very few studies have taken into account the WCO collection stage with even less consideration being taken into account for the land use impacts driven by the biofuel crop production. The life cycle energy and carbon assessment results of WCO collection varied because of the differences countries landscape, as well as economic assessment Hence, it is a necessary to take WCO logistic into account for life cycle assessment for biodiesel process in a specific location for a particular country in order to fully understand the economic and environmental impact from the biodiesel process

2.2.6 Economic assessment

2.2.6.1 Biodiesel production costs

Many studies have been conducted and reported on the feasibility of biodiesel refinery production. The recommendations from previous literature showed that careful management of the process is essential for maintaining high efficiency of the plant and high-quality biodiesel production. The primary considerations on the cost of manufacture of biodiesel are capital and operation costs, feedstock cost, by-products credit and the yields and quality of the biodiesel product. The petroleum diesel price provides the baseline against which the cost of biodiesel production must be compared. The biodiesel selling price should be lower or equal to petroleum diesel price to enhance the competitiveness in the market.

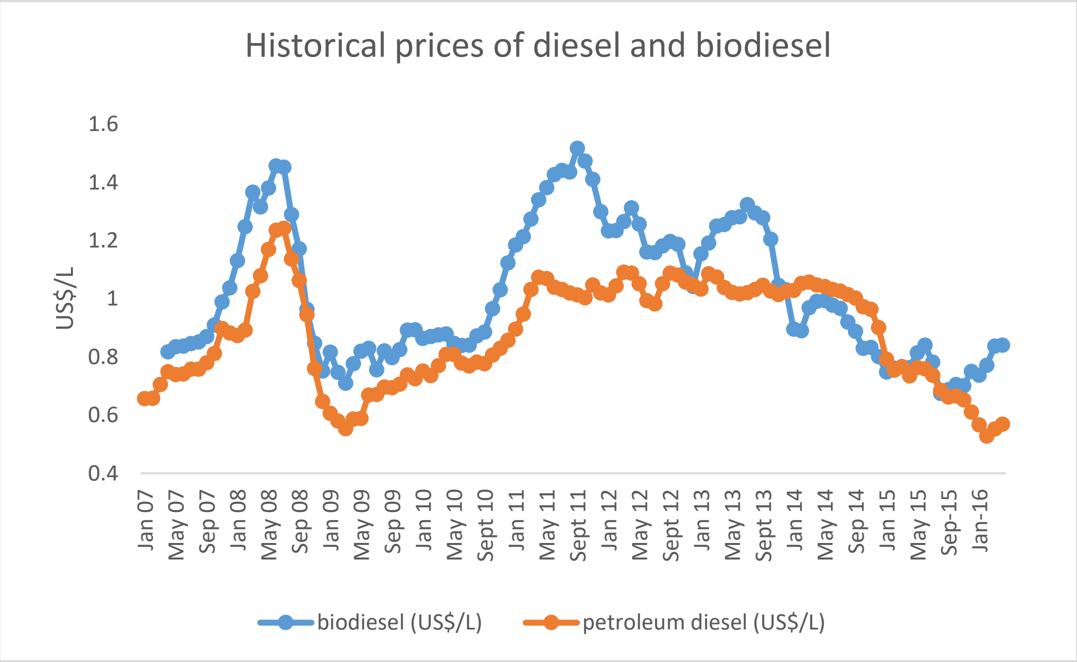

Figure 2-4: Historical prices of diesel and biodiesel in the USA (U.S.Energy Information Administration, 2016)

Since the early developing stage of biodiesel in the 1990s, the biodiesel production has become worldwide. This has the resulted in historically high oil prices and increasing awareness of energy security. The biodiesel production increased sharply in about twenty centuries. In 2005, the world biodiesel production had reached 4.16

billion litres (pacific biodiesel, 2016). Thereafter, the prices of both types of diesel are subject to the market fluctuation as shown Figure 4-2 (U.S.Energy Information Administration, 2016).

In Australia, the price of biodiesel blends will vary according to bulk supply prices for biodiesel and diesel and it is generally more expensive than petroleum diesel. The Australian Government had increased biodiesel exercise to 19.1 cents per litre from 1 July 2011 to 1 July 2015 in order to encourage the alternative carbon neutral fuels (Economic Development and Infrastructure Committee, 2008).

The price of the feedstock is the main driving force of the production cost in the biodiesel industry. Many literature have reported that the feed cost occupies almost 70-75% of the total operational cost (Anuar & Abdullah, 2016; Azad et al., 2016; Bhuiya, Rasul, Khan, Ashwath, & Azad, 2016; Biofuel Economy, 2009; Jayasinghe, 2016). To reduce the feedstock price, researchers have made a lot of efforts in the aspect of increasing the varieties of the feedstock and utilising the waste. The waste cooking oil used the least energy in the feed preparation stage. In Australia, according to Tom and co-workers, the WCO price as feed of biodiesel production was $0.20/L based on the Australian Tax Office estimation and the production cost was $0.35 /L with $0.06/L glycerol revenue in 2007 (Beer et al., 2007). In another study, O’Connell et al. compared waste oil, tallow and canola, and found that the lowest production cost (AUS $0.45/L) is from waste cooking oil to biodiesel in Australia (O'Connell, 2007). However, not much research has been conducted on the use of biodiesel feedstocks.

2.2.6.2 Bio-oil production cost

The biofuel economy is shaped by many factors such as feed availability, government levy or fossil fuel market prices, etc. In 2009, biomass provides about 45 ± 10 EJ, which is approximately 10% of annual global fossil fuel supply (Demirbas, 2009). A few upgraded biofuels have caught the attention for marketing prediction. The price of gas synthetic liquid fuel price has been up to $0.50/L biofuel (US $60 per barrel). According to Demirbas, the high-quality synthetic fuels from woody biomass are expected to be competitive at crude oil prices above $0.38 /L biofuel (US $45 per barrel) (Demirbas, 2009).

Although crude bio-oil from biomass is still an infant product, most of the commercial trial companies have tried to upgrade crude bio-oil to high-quality biofuels. The market price for crude bio-oil is volatile from year to year depending on the upgrading technologies. Most of the technologies today have total production costs greater than \$1.04/L biofuel with gasoline price only at \$0.52/L in 2015 (Tyner, 2015). However, in America, Brooks predicted the crude bio-oil price could be \$0.39/L bio-oil (US \$45/barrel bio-oil) because due to the most dynamic technologies can achieve great performance on biodiesel JetA (Brooks, 2013).

2.3 Summary of literature review and objectives of this study

Based on the above literature review, several key conclusions are summarised as follows:

Firstly, bio-oil from biomass via the pyrolysis process is a promising technology and numerous researches have been conducted in various aspects, such as developing new methods, or the invention of new reactors or new columns to suit the purpose. However, the analysis of energy consumption has focused mainly on the equipment within the pyrolysis process and the agroforest growing stage has hardly been assessed. Consequently, very few literatures have assessed the energy ratio on agriculture and forestry activities separately in Western Australia.

Agro-forestry is a multi-farming activity which combines agriculture and forestry in one land for local land improvement. It is of great importance to assess the energy footprint of bio-oil process which includes the agro-forest farming practice because energy footprint is a significant indicator of the products feasibility. In addition, the outcomes of energy footprint for agro-forest farming activities vary significantly between countries or states. It needs to be assessed based on its local geometrical condition, labour requirement and farm cultures.

Secondly, bio-oil pyrolysis process and biodiesel process's carbon footprint have been analysed thoroughly by many researchers, but with the emphasis mainly on the pyrolysis and transesterification processes themselves. The results from this study showed that the application of bio-oil and biodiesel has great positive impacts on the environment and also social aspects. Only a few of the previous studies have analysed the impact of land use for biomass forestry and the impact of waste cooking oil collecting logistics. Land use and land use change (LULUC) is a significant source of greenhouse gas emissions to the reductions from the atmosphere. It is strongly related to local rainfalls, landscape and lands current conditions. However, previous biomass life cycle studies did not include GHG emissions from LULUC. There are no carbon footprint studies that have considered the land use change from abandoned land to farm land. Therefore, expanding the study on the GHG emissions relating to LULUC is imperative for a complete life cycle assessment of biomass.

Previously only a small number of studies on biodiesel derived from waste cooking oil studies have considered the waste cooking oil collection stage and logistics. The studies found that the collection of the waste heavily relied on the local metropolitan layout. Therefore, it is a necessary to assess the biodiesel process and include the carbon footprint from logistics.

Thirdly, knowing the production feasibility of bio-oil and biodiesel from biomass and waste cooking oil, as well as the economic analysis is a necessary part of business planning. The ambitious goal of carbon research is replacing fossil fuel by biofuel in the near future. Many studies focused on the market of upgrading crude bio-oil and glycerol but the technologies are not mature enough to cope in the commercial market and the production cost of crude bio-oil would heavily rely on the methods and technologies.

Numerous researches have been conducted on crude bio-oil prices, but only a few reports could be found which predicted the price. Recently researchers have been paying attention to the blending of crude energy oil to create new energy fuel instead of upgrading the crude bio-oil and glycerol which is uneconomical. Therefore, determining the production costs of bio-oil, glycerol and blends is not avoidable.

Fourthly, water footprint did not gain attention from the researchers due to the complexity of the water flow. However, it is worthwhile determining the water footprint of forestry and agriculture, especially when the land use change involved.

Therefore, further study is required to fill the above research gaps as identified from the literature review. Nevertheless, it is impossible to fill all the research gaps in this study. The scope of this study focuses mainly on Life Cycle Assessment on energy, carbon and water footprints and biofuel economic assessment. The detailed objectives of this study are:

1) To evaluate the best location of the proposed bio-refinery plant by counting land, labour and infrastructure prices and availability;

2) To analyse the energy footprint for biofuel processes by counting all the parameters of energy inputs and outputs such as labour energy requirements, farm activities, the process and the optimised feed collection route;

3) To analyse the carbon footprint for the biofuel processes by counting not only all the above parameters and also counting the Land Use and Land Use Change Forest (LULUCF) carbon emissions;

4) To determine the water footprint for phase farming with tree system on unique Australian geometrical landscape;

5) To develop a new process that combines bio-oil and biodiesel plant, aiming to convert crude bio-oil and crude glycerol into value-added new product;

6) To evaluate the economic viability of value added crude by-product glycerol from biodiesel processes by simulating two new processes, (a) Bio-oil/Methanol/Glycerol (BMG) process and (b) Bio-oil/Glycerol/Biochar (BGB) process.

Chapter 3 Methodology

3.1 Introduction

This chapter outlines the overall research methodology to examine the energy, water and carbon footprints of biofuels production under unique Western Australian conditions. A few simulations have been conducted to achieve the objectives of this study. The details of simulations are given as follows.

3.2 Methodology Overview

Three biofuel processes are considered in this study; they are (a) biodiesel from waste cooking oil undergoing transesterification reaction, (b) bio-oil from mallee biomass undergoing pyrolysis reaction, and (c) blending fresh methanol with by-product (crude glycerol) from biodiesel process and bio-oil from biomass process to form a new evolution fuel. A series of systematic simulations were carried out, including:

- Phase farming with trees system was simulated and all farming activities and land-use change were accounted for in the energy, carbon and water footprint;
- A survey of local waste cooking oil collection in the metropolitan area was conducted for transport modelling;
- Biodiesel from the waste oil process was simulated and the bio-refinery plant location and best transport route were analysed under the unique Western Australian condition;
- The blending process of bio-oil, methanol and glycerol was simulated and the economic assessment was completed by employing the Aspen Process Economic Analyser.

In this study, four simulators were employed and the local data were collected to ensure the results represented the Western Australian condition. The overall methodology for achieving these study objectives is illustrated in Figure 3-1 with detailed explanation in the following section.

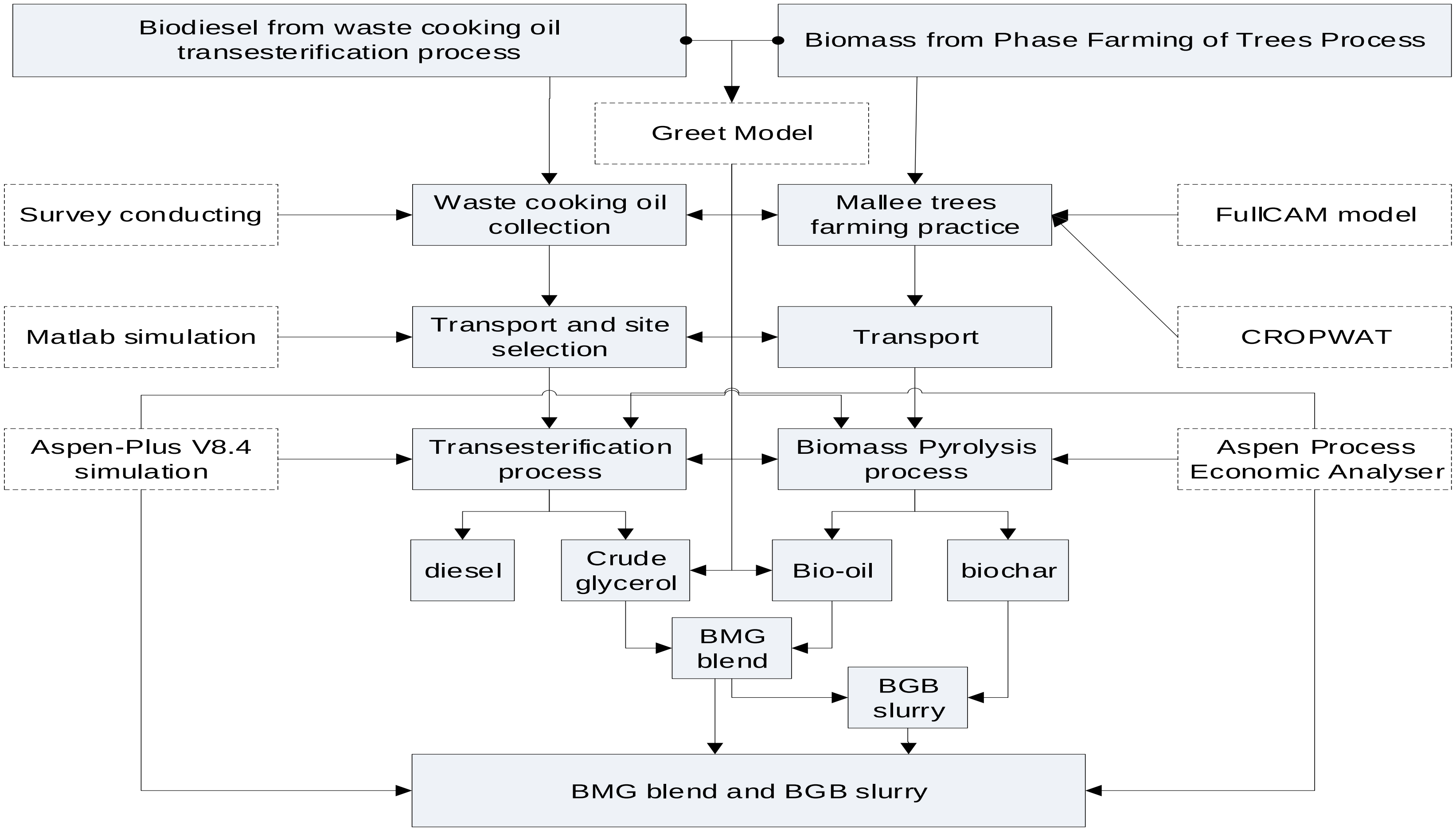

Figure 3-1: Research methodology and linkage with the research objectives to be achieved in this study

3.3 Methodology of life cycle assessment

To achieve the main objectives outlined in Section 2.3 of Chapter 2, the Life Cycle Assessment (LCA) is employed to estimate the environmental impacts through all the human activities, such as the product and process over its entire life cycle, from cradle-to-grave. The ISO 14040 Standard outlines a framework for LCA that includes goal and scope, inventory analysis, impact assessment and interpretation for products or services. Typical stages of LCA of any products require inputs such as raw materials, fuels, electricity and water. The outcomes of those stages are the consequent exchange of substances to the environment. LCA is widely used for evaluating the environmental impacts. In addition, under the same LCA principle, the energy, water and carbon footprints are all analysed in this study.

The goal of LCA in this thesis is to analyse the fuel options in Western Australia via the "cradle-to-grave" consideration. In order to best serve that goal, the boundaries of biofuel processes need to be drawn, and these details are described in Section 3.2.2. Once the system boundaries are established, the inventory analysis may be performed in order to quantify the feed materials for the products. In this way, the entire life cycle of the process assessment can be observed. Six models are employed to quantify energy, water and carbon footprints' of biofuel processes. They are FullCAM model, GREET BETA model, CropWAT, Matlab, Aspen Plus and Aspen Process Economic Analyser. Both FullCAM and GREET model are used for life cycle carbon assessment, CropWAT is used for life cycle water assessment, Matlab is used to determine the best route of transport in metropolitan areas and site selection, Aspen Plus is used for life cycle energy assessment, and the Aspen Process Economic Analyser is used for life cycle production cost assessment. The details of these models are described in the following sections.

3.3.1 Modelling biomass from phase farming with trees production process

Phase farming with trees (PFT) is an alternative approach to incorporate short rotation of trees with agriculture. This system relies on fast-grow native species and the manipulation of silviculture to produce biomass (R. J. Harper et al., 2007). Harper et al. suggested that the tree/cropping rotation in PFT should rotate 3-5 years of trees, followed by 11-20 years of agriculture. The design of this PFT rotation configuration is based on the experiments at Wickepin and Corrigin. Happer and co-workers have planted native trees at different densities at randomized blocks. The soil moisture deficit was thoroughly determined from the experiments (R. J. Harper et al., 2014). Therefore in this study, the PFT system is assumed as 5 years woody biomass plantation, followed by 10 years agriculture production as illustrated in Figure 3-2.

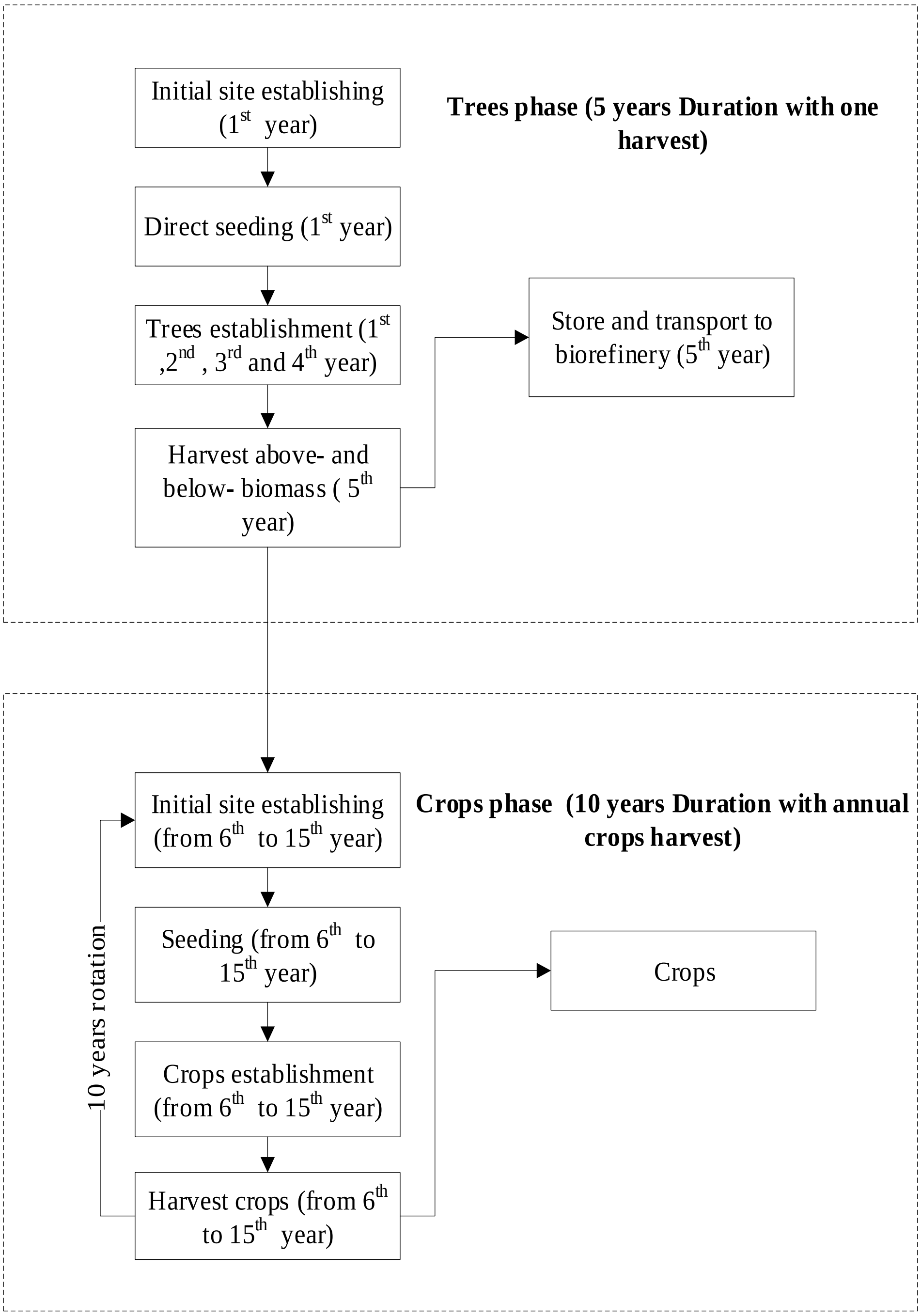

Figure 3-2: The system of Phase Farming with Trees (PFT)

3.3.1.1 Life cycle water inventory (LCWI) of biomass from PFT process

CROPWAT Version 8.0 is a program that uses the FAO (2004) Penman-Monteith method for calculating reference crop evapotraspiration. It is applicable to both annual and perennial crops, where trees can be considered as perennial crops (Mekonnen & Hoekstra, 2011).

In this study, all local data were used for water footprint calculation. The blue and green water data were adapted from government data and literature. The grey water is not included in this study due to lack of data. The accumulated data on daily crop evapotranspiration (ETc in mm/day) over the growing period of the plants were adapted data from the Australian environment department as presented in Table 3-1. The Lake Grace station is the station close to York town which is the bio-refinery plant location. The location selection will be discussed in Section 5.4.2.

Table 3-1: Lake Grace WA station average of monthly meteorological data

Station Name: Lake Grace								
Altitude: 295 m Latitude: 32.33 °S Longitude: 117.80 °E								
Month	ETo 0000-2400 (mm)	Rain 0900-0900 (mm)	Maximum Temperature Max (°C)	Minimum Temperature min (°C)	Relative Humidity max (%)	Relative Humidity min (%)	10m/Wind Speed (m/sec)	Solar Radiation (MJ/sqm)
Jan	8.4	0.2	32.9	15.8	80.5	22.7	4.9	28.9
Feb	7.1	0.7	30.6	15.1	79.5	27.1	4.9	25.8
Mar	5.6	0.1	29.0	15.4	78.8	29.0	4.2	19.3
Apr	3.7	1.6	24.7	12.3	85.5	35.7	3.2	14.8
May	1.9	1.6	18.9	10.4	94.9	59.2	3.4	10.1
Jun	1.8	0.5	17.0	5.9	91.3	51.2	3.4	9.6
Jul	1.7	1.8	15.7	6.4	93.7	58.0	3.9	9.6
Aug	2.4	1.4	18.8	6.9	91.6	47.6	3.3	12.0
Sep	3.2	1.2	21.0	8.1	92.5	43.9	3.9	16.4
Oct	4.5	2.8	24.6	10.5	89.3	34.9	4.0	20.6
Nov	6.2	1.8	27.7	12.5	86.7	25.6	4.3	23.8
Dec	6.9	0.0	28.7	12.8	84.2	26.3	4.8	25.7

Note: Data was adapted from Bureau of Meteorology. http://www.bom.gov.au/watl/eto/

The initial soil condition, water deficit, and the forest growth figures were adapted from the unpublished data of Harper and co-workers (Richard J. Harper, 2014; Richard J. Harper et al., 2014) shown in Table 3-2.

The water energy footprint (m^3/GJ) is calculated in two steps. In Step 1, the reforest energy crops water requirement in a specific area was calculated by applying the FAP Penman-Monteith method (Allan, 1998). Step 2 involves combining the calculation of the total biomass dry yield in energy form from energy footprint analysis in Chapter 4, followed by the discussions of final results.

Table 3-2: Forest growth figure and initial soil condition

General tree growth and soil data	
Total available soil moisture	300 mm/meter (Richard J. Harper, 2014)
Maximum rain infiltration rate	1 mm/day (Richard J. Harper, 2014)
Maximum rooting depth	800 centimetres (Richard J. Harper et al., 2014)
Initial soil moisture depletion	10% (Richard J. Harper et al., 2014)
Initial available soil moisture	270 mm/meter (Richard J. Harper et al., 2014)
Crop coefficient (k_c)	0.90 (Al-Najar, 2011)
Effective rainfall (P_e)	0.75 (Farmwest, 2011) *

*During the dry season, rainfall less than 5 mm may not add any moisture to the soil reservoir

3.3.1.2 Life cycle energy inventory (LCEI) of biomass from PFT process

The system modelling exhaustively accounted for all activities through the processes, which may involve direct (use of farm machinery and transport equipment, fertilizer application, etc) or indirect (production of fertilizers and agrochemicals, production of vehicle fuels, manufacture of farm machinery and transport equipment, labour, etc.) energy inputs.

The energy consumption was converted from dollars to energy by means of energy per capita. Revegetation Project Modelling and Costs involved project planning and management, transport costs and fuel consumption, seed and tree guard costs and site supervising. After all the energy evaluations had been done, the energy was converted to a universal unit for comparison and benchmarking. It is widely accepted that the energy unit is energy consumption (PJ) in current year divided Gross Domestic Product (GDP) to obtain an energy value as dollar-to-energy conversion. The total Australian energy consumption in 2012 was 59459 PJ, and GDP was 1473227 dollars. Therefore, the energy conversion factor is 40.359 MJ/$ in 2012 (Australian Bureau of Statistics, 2012b; Schirmer & Field, 2010; M. Wang, 2012) . The energy ratio concepts were developed by Wu and co-workers (Wu et al., 2008) for evaluating the energy performance of energy crops. The net energy balance ratio of a biomass can be defined as the ratio of the energy intensity of the oven-dried biomass in native trees to the non-renewable energy used in its production, i.e., energy output/energy input (Wu et al., 2008). The net energy balance ratio (R) is defined by the following equation.

$$R = \frac{Total\ energy\ intensity\ in\ E.occidentalis\ tree\ on\ oven\ dried\ basis}{total\ non-renewable\ energy\ used\ in\ its\ production}$$

Monetary costs such as labour costs are converted to the energy and GHG emission values using the Australian data on the national average energy consumption per unit gross domestic product (Schirmer & Field, 2010). All input and output parameters were converted to energy dimensions to enable direct comparison. In this study, the High Heating Value (HHV) of the fuels is used to calculate direct energy inputs and efficiency. The details of data collection are discussed in Chapter 4.

3.3.1.3 Life Cycle Carbon Inventory (LCCI) of biomass from PFT process

The overall LCCI in this study consists of two parts: one is biomass establishment (including seed, direct seedling, planning, site preparation, planting, management and transport); the other is carbon sequestration occurring on land use and land-use changes forestry (LULUCF) sector.

The GREET model, developed by the Argonne National Laboratory in the USA, is a widely used analytical tool that simulates the energy use and emissions of various vehicle and fuel combinations. The energy and GHG emissions associated with indirect inputs such as agrochemicals were thus adapted from the GREET BETA 2014 model. The FullCAM model is employed to analyse the carbon footprint in LULUCF sector. Details of these two models are described in the following sections.

1) GREET BETA model of biomass establishment of PFT process

The GREET BETA 2014 Model is employed in this study for analysing carbon footprint of biomass from PFT process production. This study used a cradle-to-gate analysis, meaning that the product's life cycle was considered from preparing land and buying seeds to delivering the green biomass at the farm gate. Waste disposal components were not considered in this study. The data of GHG emissions associated with reforest farming projects, such as production, packaging, fertilizer, and transportation are adapted from the GREET BETA 2014 model (M. Wang, 2012). Data for those during the maintenance, disposal, and manufactory of the machinery, such as harvester, tractors, trucks and cars are obtained from the literature (Department of Jobs and Small Business, 2019; Willian Lazarus & Selley, 2005; William Lazarus & Selley, 2009; Mikkola & Ahokas, 2010; Schirmer & Field, 2010). The logistics were determined on the basis of plant capacity to calculate the required transport equipment. The costs of fuel and labour, and energy data were adapted from the Australian Bureau of Statistics. The results from these simulations will be illustrated and discussed in Chapter 7.

2) FullCAM model of biomass from PFT system in LULUC sector

The FullCAM model has been employed for determining the carbon emission in this study which was developed by the Australian Department of the Environment (Department of the Environment and energy, 2013). This model provides enormous information on forestry and agriculture spatial data, the plant species growth data and spatial weather data (Department of the Environment and energy, 2012; Schirmer & Field, 2010). This study simulated a total of 5 years production ranging from 2016 to end of 2021 and a few assumptions has been made for simplicity. The results will be shown and discussed in Chapter 4.

Assumptions of the simulation are:

- The longitude and latitude of the location are -32.7818^{o} S, 117.4990^{o} E, respectively.

- Out of the total saline farm abandoned land, 100% of severe and moderate saline land is replanted and 50% of low saline land is replanted (Cleary et al., 2009). That is because carbon stock of a managed forest is a function of site productivity and silvicultural management (i.e., stocking rate, species, pruning, thinning).
- The abandoned scald lands are infertile, saline and eroded, where the lands had lost the organic matter.
- The carbon flux is ignored in this study, and therefore the initial carbon baseline was set as zero (IPCC, 2006).
- Four plant species are considered: *Eucalyptus globulus, Eucalyptus occidentalis, Pinus radiata and Eucalyptus mallee.*
- All trees grow as low open forest.
- The abandoned scald lands are infertile, saline and eroded, wehre the lands had lost the organic matters. Hence the carbon flux was ignored in this study, and therefore the initial carbon baseline was set as zero (IPCC, 2006).
- The carbon footprint from Land Use and Land Use Change (LULUC) was calculated based on annual biomass changes in order to achieve high consistency in footprint comparisons. This comprised an annual change in carbon stocks in above- and below-ground biomass except fine roots remain in soil (Wu et al., 2008).
- The annual change in carbon stocks in dead organic matter and annual change in carbon stocks in soils.

3.3.2 Modelling biodiesel from waste cooking oil production process

3.3.2.1 Biodiesel from waste cooking oil process system boundary

In the biodiesel production process, waste cooking oil (WCO) was collected from Perth metropolitan areas and transported to the ideal location of biodiesel plant, then mixed with methanol and sulphuric acid to convert WCO to methyl esters. Typically waste cooking oil contains 2-7% of free fat acids (FFA) (Morais et al., 2010). According to Morais and co-workers, WCO is needed to pre-treat FFA before the esterification process, and they recommended that the alkali-catalysed process has less environmental impact when compared to the acid-catalysed process. So in this study, the alkali-catalysed FFA treatment biodiesel process is employed (Morais et al., 2010).

This biodiesel production from the WCO process consists of WCO collection, plant location selection and production process. The by-product glycerol is utilised by blending with bio-oil and methanol to form a new evolution fuel. This blending process will be discussed in Chapter 6. To best serve the objective outlined in Section 2.3, a waste cooking oil survey was conducted and Matlab was employed to determine the best route for collecting WCO. The best bio-refinery plant location was also analysed. Details of the methods are reviewed in the following subsections.

3.3.2.2 The survey of quantifying the WCO

This survey was designed specifically to quantify the waste cooking oil resources that are generated from all restaurants and fast food chains in Perth metropolitan areas. The survey was conducted over a period of several months and the data was collected for different types of restaurant. The survey responses were grouped by five-star restaurants, fast food chains, fish & chips shops, private canteens and Cafés. Those four groups response indicated the series of statements on the rate of throughputs and flow directions for WCO.

The survey was created and distributed by listing questions that reflected the interests of feedstock. The questionnaires were distributed by an initial telephone call to prospective survey participants. All the responses and non-responses were noted and reflected in the results and discussion. The main focus of the survey was to obtain the quantity of WCO in Perth metropolitan areas and determined the trends of feedstock stability. The results are grouped according to the restaurant type. The survey also gives the location of all the restaurants which is necessary information for modelling the best WCO collecting route. The method of modelling the best route will be described in the next section.

3.3.2.3 Life cycle energy inventory of biodiesel from WCO process

The energy inventory includes the best route of WCO collection, plant location, and the process itself. This is achieved by Matlab simulator, Aspen Plus V8.0, GREET

2014 and Holger Nickish economic analyser. The details are described in the following sections.

1) Matlab modelling of the best route of WCO collection and tortuosity

The waste oil collecting truck travels to all the restaurants in the Perth city area. The best and most economical way of collecting waste oil from different restaurants is to visit all the restaurants once and return back to the beginning of the trip. Since restaurant locations can be found from the *Latitude and Longitude of a Point* website ("Latitude and Longitude of a Point," 2012), thus a straight distance can be calculated between the two points. The use of 2D multipoint integration program is satisfied in this case.

Initially 191 restaurants were analysed and 191 pairs of latitude and longitude as node points were extracted to form 2 by 191 matrix, then Matlab was used to solve this complex matrix. The main Matlab equation that was used as follows

```
reshape(sqrt(sum((xy(a,:)-xy(a',:)).^2,2)),N,N),
```

Matlab iterates the calculations until the smallest result is shown, then Matlab program compares and adds the shortest distance to form a route. After 9951 iterations, the results are shown in Chapter 5.

To get the best possible results, the tortuosity factors are also calculated by using the ratio of actual travel distance via the road to the shortest straight line distance. The real distance data is adapted from MainRoads (Mainroads, 2013), and the longitude and latitude of individual locations were adapted from the geographic website (Trainer, 2012). However, restrictions relating to one-way turning and speed limits were not considered in this study.

2) Aspen-Plus Modelling

ASPEN PLUS V8.4 was used for modelling the three overall processes with this survey and previous research data input (Aspentech, 2016). Two new processes are designed in Aspen simulator, one is by blending crude bio-oil, glycerol and methanol to create a special type of fuel, the other one is by blending crude bio-oil, glycerol and biochar to create a slurry fuel. For the new processes, the biomass, the blend and the slurry data were adapted from the work of Yun et al. and Zhang et al. (Yu, 2016; M. Zhang & Wu, 2014) The traditional waste oil to biodiesel process data and equations are available in the literature (Morais et al., 2010). The size of the process equipment was analysed using ASPEN PLUS. Since the biofuel recycling process involves non-ideal liquids hence NRTL (non-random two liquid) was selected as the base simulation method with steady state assumption.

3) Modelling of optimal plant location

The costs were performed in a similar fashion as the process design. The economics analysis was simulated by the Aspen Process Economic Analyser. All costs estimated were based on 2016.

The Holger Nickish economic analyser was intended for determining the best location for a new bio-refinery plant in Western Australia. All the sensitive factors have been considered thoroughly, and these include final distribution network, personnel commuting, government legislation, infrastructure availability, plant maintenance and environmental abatement. Since production cost is the main factor in determining the feasibility of the plant business, the plant location was simulated under the same plant capacity and operation conditions, and compared to the production cost of each location.

The Western Australia Map is drawn using the Matlab Map program. The real distance was used for analysing freight and related costs, but the real distances from Perth CBD to towns or localities were found from Mainroads Western Australia (Mainroads, 2013). The infrastructure data was adapted from the Australian Government Productivity Commission (Productivity Commission of Australia Government, 2013) and Australian infrastructure statistics – yearbook 2013 (Department of Infrastructure and Regional Development, 2013). The land price guide was adapted from the Government of Western Australia Department of Housing (Government of Western Australia: Department of Housing, 2014). The significant qualitative variables for the plant location were capital costs, maintenance, raw material costs and operation costs (Pérez-Fortes, Laínez-Aguirre, Bojarski, & Puigjaner). These variables were derived from the Holger Nickish economics analyser (Nickish, 2003).

3.3.2.4 Life cycle carbon and water inventory of biodiesel from WCO process

The GREET BETA model is employed to assess the carbon footprint of biodiesel from WCO process by adapting local data. First, the GREET Model is built based on transportation distance and transesterification process. From Matlab simulations, the total transportation distance was 593 km per day, which includes the distance for the collection and transport of WCO to the bio-refinery plant. This simulation will be discussed in Chapter 5. The transportation distance is the result of the WCO collection distance in the metropolitan area plus the distance from metropolitan to York town. The transportation is assumed using heavy duty truck only in GREET simulation in this study.

The transesterification process is also simulated by ASPEN. The carbon life cycle assessment of the transesterification process is simulate by GREET. A few assumptions have been made for simplify the simulation: (1) the he phosphoric acid is assumed to be used as the acid catalyst, (2) the feed methanol is 99% purity, (3) the plant operates 300 days per year, the non-production days are for maintenances and (4) the solids in the WCO is assumed as zero.

3.3.3 Modelling bio-oil/methanol/glycerol (BMG) blending process

3.3.3.1 The boundary of the BMG blending process

This is a simple blending process that just involves blending glycerol, methanol and bio-oil to form a new type of fuel, namely bio-oil/methanol/glycerol (BMG). It includes drying biomass, pyrolysis reaction and blending processes. Since crude glycerol is derived from biodiesel process and biomass is from the PFT system, then blend with bio-oil from biomass pyrolysis process and fresh methanol to achieve the desire proportion.

3.3.3.2 Modelling methods

The modelling methods are similar to those for Section 3.3.1 and 3.3.2. Both Aspen Process Economic Analyser and Holger Nickish economic analyser are employed for economic assessment of the blending process. Aspen Plus v8.0 is used for assessing the energy footprint.

Table 3-3: High heating values of various fuels

Fuel	HHV (MJ/kg)	Reference
Biomass from forest	20.58	(U.S.Department of Energy, 2016)
Bio-oil from wood	19.0	(Pyrolysis char Heating Values, n.d.; M. Zhang, 2015b)
Methanol	22.88	(U.S.Department of Energy, 2016)
Biochar from lignin	31.3	(Pyrolysis char Heating Values, n.d.)
Biodiesel	40.16	(U.S.Department of Energy, 2016)
BMG blend	19.08	(M. Zhang, 2015b)
BGB slurry	20.26	(W. Gao, Zhang, & Wu, 2016)

GREET is used for calculating the carbon footprint that consisting the tree farming, harvesting, pyrolysis reaction, esterification reaction, blending or mixing stages and transportation between each stages. These footprints will be discussed in Chapters 4 and 5.

The pyrolysis process data are adapted from Yu’s unpublished data (Yu, 2016); and these are (a) 21.03 GJ of green mallee biomass produces 10.39 GJ bio-oil, and (b) 7.02 GJ biochar is produced from the fast pyrolysis process. Among the total biochar production, 1.69 GJ biochar was used for equipment energy consumption (Yu, 2016). The mass and energy balances will be discussed in sections 4.3 and section 5.9.

High heating value is defined as the amount of heat released by the unit mass or volume of fuel once it is combusted and products have returned to a room temperature. It includes the latent heat of vaporization of water. Therefore, the high heating values are used in this study because all the final products from the processes are designed to store at room temperature. All the heat from combustion process are utilised to heat the feed and reactors. These data are presented in Table 3-3.

The practical application of biomass is likely to use the whole-tree biomass as feedstock, so, in this study, the mallee biomass includes above- and below biomass. Also, as different species of the tree consist of various biomass components, therefore, it is important to estimate the high heating value of the biomass based on the composition of the main elements of the whole tree. From previous research of mallee biomass properties on dry basis (X. Gao, Rahim, Chen, & Wu, 2017) as shown in table 3-4, the calculated high heating value (HHV) for whole mallee tree is 21.1 MJ/kg dry basis.

Table 3-4: High heating value of mallee biomass

Mallee biomass wt% dry basis [a]	**Leaf**	**Wood**	**Bark**
C	59.1	48.9	48.9
H	7.4	6.7	5.0
N	1.24	0.43	0.26
S	0.12	0.02	0.03
Cl	0.24	0.05	0.41
O (by difference)	31.9	43.9	45.4
HHV (MJ/kg) [b]	23.4	20.1	18.9
Whole tree biomass [c] HHV (MJ/kg)		21.1	

[a] The data of ultimate analysis are adapted from literature (X. Gao et al., 2017).

[b] The HHV is calculated based on the composition of main elements (in wt%) C, H, and O, the equation is HHV (MJ/kg) = -1.3675 + 0.3137C + 0.0318O* (Sheng & Azevedo, 2005)

[c] The "whole tree biomass" is assumed as a mixture of three components at a mass ratio of 15% bark, 35% leaf and 50% wood (dry basis db) (X. Gao et al., 2017), hence the equation of the "whole tree biomass" HHV (MJ/kg) = 0.15 HHV(bark)+0.35HHV(leaf) + 0.5HHV(wood)

Chapter 4 Biomass Production by Phase Farming with Trees

4.1 Introduction

Planting deep-root trees to overcome salinity problems is part of the salinity management in Western Australia as mentioned in many literature reviews (Sochacki et al., 2012; Wu et al., 2008; Yu et al., 2009). For example, planting fast-grow native trees in wide-spaced narrow belt configurations is integrated with existing agricultural activities (Wu et al., 2008). Utilising short rotation or fast-growth native trees as woody bio-oil feedstock is a triple win opportunity to repair scald soils and to increase reforest areas whilst producing renewable fuels (Sochacki et al., 2012). After the bio-oil from biomass concept was established and the technology has matured, a new reforest farm seemed like a lucrative business because the process has the ability to recycle all the wooden wastes. In addition, planting native forests can provide an opportunity to return the land to its original landscape and to enrich the biodiversity. The widespread development of woody bioenergy and growing native Australian plants, in particular, depends on the parameters of the landscape, the severity of the salinity, native plant species and water availability along with social and economic sustainability (Yu et al., 2015).

A series of recent studies on mallee belt plantation by Wu et al. have shown that mallee biomass supply chain is economically viable, and the energy and carbon footprints of mallee belt biomass production are environmentally sustainable (Yu et al., 2009; Yu et al., 2015; Yu & Wu, 2010). It is known that reforesting mallee biomass is one of the salinity managements in addition to sequestering greenhouse gases emissions. Yu et al. have conducted life cycle assessments on mallee biomass production that include the land-use effect (Yu et al., 2015).

Nevertheless, such a belt configuration does not suit all landscapes such as water logged areas, valley floors, and areas of broken slope (Lambert, 2000). Similarly, there are likely to be competitive effects between belts of trees and adjacent crops, particularly in dry years (Sudmeyer, n.d.) and partial reforestation may be insufficient to restore catchment water balance (R.J. Harper et al., 2014,; George, n.d.). To increase the efficiency of water management while producing biomass in these areas, Harper and co-workers have proposed a phased reforestation system, termed Phase Farming with Trees (PFT), under which trees are grown for 3 to 5 years (tree phase) and crops are planted in a subsequent 10-20 year agricultural phase (R. J. Harper et al., 2007; R. J. Harper et al., 2014; Sochacki et al., 2012). This PFT process was introduced in Section 3.3.1.1 and the process was shown in Figure 3-2.

Previously the research has focused on carbon mitigation on scald lands, soil water deficit and biomass productivity. However, the research is far from sufficient to form a complete scald land management. Particularly, since the dynamic changes of carbon and water content in soils are largely unknown, thus the life cycle carbon footprint of biomass production is also unclear, especially in the uniquely Western Australian climate condition.

Therefore this study aimed to focus on drawing a boundary of biomass production system from seeding to biomass on the farm gate for life cycle assessment. The LCA results are then used to determine the carbon energy and water footprints of the overall process. This study provides a detailed account of the native woody biomass production, which is supported by field experience from Murdoch University. The details of the PFT system boundary are described in the next section.

4.2 The boundary of Phase farming with trees (PFT) system

Biomass production is quantified with regular growth rate in semi-arid climate on abandoned salinized farmlands. According to the study by Cleary et al., the salinized land should be planted with deep-root native trees (Cleary et al., 2009). Varieties of native vegetation should be planted in salinity-affected lands to maintain the ecosystem. For instance, many species have been planted in research experiments, e.g. Ritson et al. planted *mallee euculypts*, *melaleuca*, *Atriplex*, *acacia species and* *casuarina obesa* (Ritson, Clarke, Killen, & Jeffery, 2015), and Harper and co-workers planted and examined *eucalyptus globulus*, *eucalyptus occidentalis and pinus radiata* (R. J. Harper et al., 2007).

They found that the biomass production is highly dependent on the land condition but not on the yield of the species. Therefore, to simplify the complexity of the simulation, this study assumed 100% of the above mentioned saline abandoned land was used for replanting mallee bushland, and the use of mallee was feeds for the biomass refinery plant. The typical biomass from PFT field data and parameters are described in the following subsections.

It is important to specify that the 10 years agricultural planting stage is not included in the footprints assessments because the crops are the food for human beings in this case. Therefore, biomass from the agricultural stage only comprised the agricultural biomass waste which is collected annually and sent to a bio-oil refinery for bio-oil production.

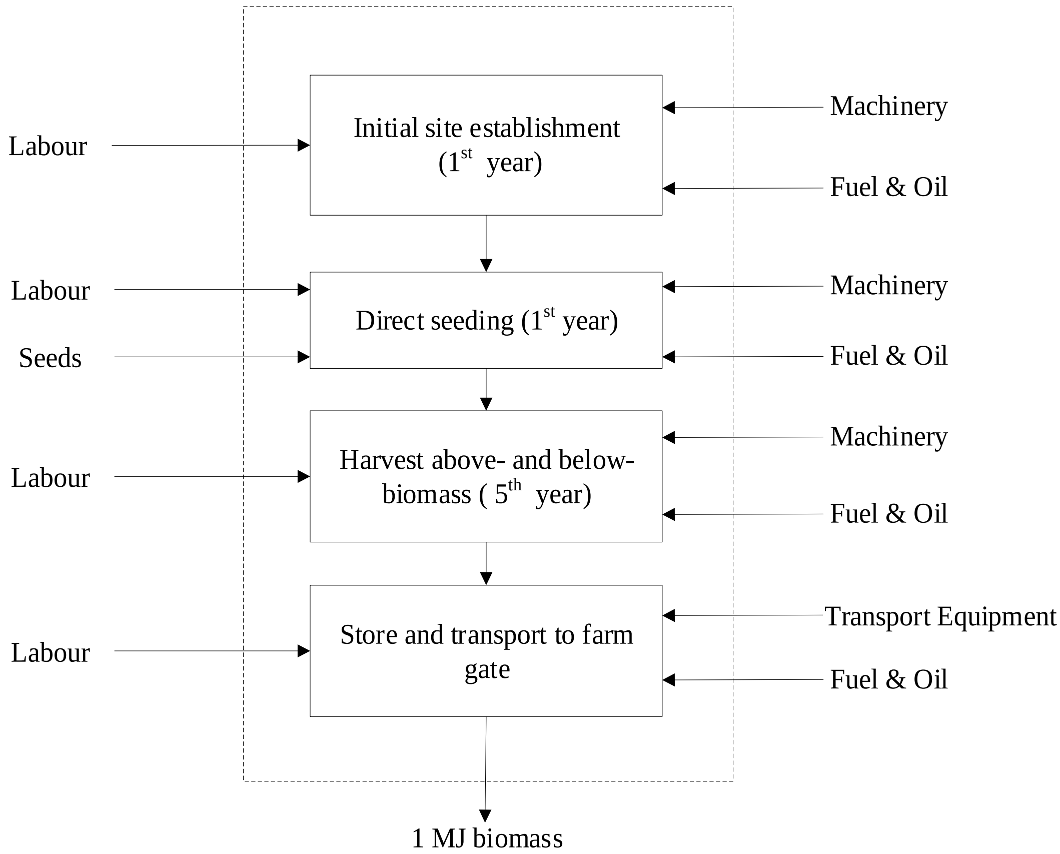

Figure 4-1: The boundary of Phase Farming with Trees (PFT) system

Figure 4-1 illustrates the overall process of PFT system boundary. The overall PFT system consists of a biomass establishment that includes seed, seeding, planning, site preparation, planting, harvesting, on-farm haulage to the farm storeroom, air drying, crushing, mulching and store at the farm gate. This study assumes that 100% of saline abandoned land was used for replanting mallee bushland, and the use of mallee is a feed for the biomass refinery plant.

4.3 Functional units

The functional unit for biomass production is 1 MJ biomass in this study. The sub-functional units of water, energy and carbon footprints are GL per MJ biomass, MJ per MJ biomass and g carbon dioxide equivalent (CO_2-e) per MJ biomass and respectively.

4.4 Life cycle impact assessments

In this study, the life cycle impact assessments evaluate the significance of the potential energy, water and environmental impacts of the biomass from the PFT system by following the ISO 14014 series guidelines (International Standard Organization, 1997). The system boundary of this LCA is from cradle to farm gate, and the details of the boundary and the conditions were described in Section 4.2.

4.4.1 Farming activities of the PFT system

The typical farming activities associated with growing woody biomass on sanitized land are shown in Table 4-1. Values of total indirect and direct energy were determined thoroughly through all activities and the output energy is the energy embedded in the dried biomass. Those activities include initial site preparation, tree planting, tree harvest (tops and roots), and transport. However, fertilizer was not used in the site experience, no sapling and coppice at the second, third and fourth year of the planting. Here, the PFT system was assumed as a 5-year woody biomass planting with 100% harvesting of both above- and below-ground biomass (coarse roots only).

Table 4-1: Life cycle inventory of mallee establishment in PFT system on abandoned salinity farmland

	Operation	Job description	Specification	Details of the input	Description of the input
1	Planning Project	Project planning and management	On site	Planning the project, visiting and surveying the site, choosing vegetation type, consulting and training of local community members, obtaining supplies, booking contractors and volunteers, supervising revegetation work and monitoring the success of revegetation	$700 per hectors [a]
2	Finance: farm insurance and taxation plan	Get loans from banks	Perth	Consulting with bank brokers 8 hrs for getting loans for purchasing/renting of land, equipment and infrastructure etc.	Perth office at $41.76/hr [b]
3	Obtain regulation & permits	Obtain business license, log into government sponsored enterprise, projects funds or sustainable scheme etc.	Perth	Meeting government officers 6 hrs for lodging into any eligible scheme or funds	Perth office at $41.76/hr [b]
4	Nursery	Seed	Perth	Purchasing seeds from Murdoch University farm institution or another nursing farm	4000 seeds, $0.40 / gramme of rainforest species, purchase price $1600 [c]
5	Pre-farming	Paddock preparation, such as weed control or removal of compaction	On site	Preparing the site, deep ripping one pass by chisel plough (3 m working width, 8 km / h), hiring skilled driver, chisel plough and labour 10 hrs site work, spraying weed control chemicals	Chisel plough, life time 2000 h, engine power 100 HP, mass 1296 kg, skilled driver cost $21.95/hr [b], tractor hire rate daily $300 [c]

				or other agrochemicals for correcting soil condition	
6	Planting	Direct sowing with correct type of precision seeder	On site	Hiring Kinseed Linkage precision tree seeder rip the soil to 50 cm depth and sow the seeds into the lines directly. One driver with 10 hrs site work	Kinseed Linkage precision seeder [d] with 35 HP Tractor, 250 kg weight, 1.33 m working width, 30 km/h, hired $300 / day [c], skilled driver, $21.95/hr [b]
7	Harvest & Mulch	Harvest above- and below-biomass at the 5th year and mulch at the same time	0.25 min/tree	Hiring tree puller attachment, attach to Bobcat 463, the mulching machine is attached the back of the tractor, for 4000 stem per ha, the total driving distance is 20 km, for 1000 stem per ha, the total driving distance is 5 km	Hire Bobcat 463 with tree puller attachment [e,], 45hp, diesel, tree pulling speed: 0.5 min/tree, mulch machine., 100 hp, feed maximum 30 cm stem.
8	Store	Store on the site	On site	Hiring mulching machine, follow the tree puller, mulching the trees instantly	Biomass mulcher, 145 HP, speed 6 km/hr [f], hire fees: $350 per day [c], one driver $21.95 per hour [b]

[a] The project cost adapted from ANU forestry revegetation project (Schirmer & Field, 2000). [b] The labour wage was selected as the median wage that published in Western Australian Agriculture sector in 2019 (Department of Jobs and Small Business, 2019). [c] Seed price was adapted from websites http://www.nindethana.net.au/Product-Detail.aspx?p=1245 and http://www.murdoch.edu.au/School-of-Veterinary-and-Life-Sciences/About-the-School/College-of-Veterinary-Medicine/Farm/(Accessed 02/04/2017) [d] The data on Kimseed precision seeder was adapted from Kimseed wetsite https://www.kimseed.com.au/Seed%20Planting/Kimseed%20Linkage%20Tree%20Planter%20Seeder%202015.pdf (Accessed 20/08/2019) [e] The data of the tree puller was adapted from Himac website https://www.himac.com.au/products/skid-steer-tree-puller (Accessed 18/08/2019) [f] The data of the mulching machine was adapted from Seppi website https://www.seppi.com/en/mulcher-mower-shredder-tiller-stump-grinder/mulchers-with-chute-for-biomass-collection/midiforst-drago.html (Accessed 18/08/2019

4.4.2 Life cycle energy impact assessment from the PFT system

In this study, the life cycle energy impact assessment evaluates the energy efficiency of the biomass from the PFT process. The details of farming activities were described in the previous section 3.2. This section conducts the energy input output and the ratio in order to quantitatively assess the energy footprint of biomass production from the PFT system. The detailed approaches for assessing the energy ratio and impacts are described below.

4.4.2.1 Energy balance analysis of biomass from PFT system

1) Input Energy Density

The energy input analysis during the reforest biomass production period was extensively developed by Wu et al. in 2008 and Mallee eucalypts was used in the Wheatbelt Western Australia (Wu et al., 2008). The detailed energy input during reforest biomass production is shown in Table 4-2

This table illustrates the detailed energy inputs during biomass production, with a tree planting density of 4000 stems/ha, a harvest cycle of 5 years, and a mean biomass yield of 19.0 dt/ha (base case). Unlike highly developed agricultural harvest implements with high capacity, currently, the biomass harvest machinery can only harvest with single narrow raw.

The primary energy inputs are divided into four categories as shown in Table 4-2, the primary energy inputs are divided into four categories: (1) 1,319 MJ/ha for site preparation and management; (2) 1,600 MJ/ha for planting, (3) 4,560 MJ/ha for harvesting, and (4) 3,771 MJ/ha for woody biomass transportation. The total energy input for biomass production under the PFT system is thus 11,250 MJ/ha, the majority (71%) of which is consumed in the stages of harvesting and transportation.

2) Outputs Energy Density

The energy output is the energy contained in trees components. The above-ground biomass includes leaves, barks, twigs and wood, whilst the below-ground biomass includes coarse roots only. The fine roots remain in the soil after harvesting. The yields of above-ground oven-dry biomass for trees were 14.4 t/ha for 4000 stems. On average, the yield for below-ground biomass was 4.6 t/ha on average (Sochacki et al., 2012), hence the average of biomass productivity was 19.0 dt/ha.

Table 4-2: Energy inputs during a forest biomass production period [a]

Activity		Energy Input (MJ/ha)
Site preparation & management		
	Machinery production, maintenance and disposal	109
	Fuel and oil use	97
	Labour	17
	Agrochemicals	1096
Planting		
	Seeds	1120
	Machinery production, maintenance and disposal	270
	Fuel and oil use	193
	Labour	17
Harvesting		
	Machinery production, maintenance and disposal	169
	Fuel and oil use	3997
	Labour	139
	Other operation costs	255
Woody Biomass transportation		
	Transport equipment production, maintenance and disposal	108
	Fuel and oil use	3447
	Labour use	216
Total		**11250**

[a] The calculation is based on mallee production in Wheatbelt (Wu et al., 2008). [b] The energy in fertilisers is a calculation based on literature (Department of Environment and Climate Change, 2008; Wu et al., 2008).

In the past decades, Richard J. Harper has researched the native revegetation in saline dry land in Western Australia. According to him, the biomass productivity varies significantly depending on planting densities, tree age and landscape position. The total biomass productivity was found to range from 9.2 to 33.3 dt/ha (Richard J. Harper et al., 2014). The biomass productivities are highly depending on the local rainfall, water catchment, underground water condition and soil condition. The main reason for the low productivity (0.5t/ha) was the long draught season in summer caused the death of the plants.

With 5-years tree farming modelling, the total biomass during one production cycle yields 19.0 tonnes of dry biomass. Based on previous research of mallee properties (X. Gao et al., 2017; Sheng & Azevedo, 2005), the high heating value (HHV) for whole mallee tree is estimated as 21.1 MJ/kg and shown in Table 3-4 in the previous section, Therefore, the total biomass energy output is 399,950 MJ/ha following the 5-year duration of biomass production, with 76% of this embedded in the above-ground biomass.

Table 4-3: Biomass productivity for each species and site with 4000 stems intensity (GJ/ha) [a]

Age of trees		3	4	5
E.globulus	upper-slope	84.4	109.6	225.9
	mid-slope	209.7	268.2	396.5
	lower-slope	217.8	315.3	360.9
E.occidentalis	upper-slope	113.9	158.4	226.3
	mid-slope	170.0	181.1	214.0
	lower-slope	243.8	331.1	440.6
P. radiate	upper-slope	113.8	236.5	465.6
	mid-slope	267.3	403.5	607.9
	lower-slope	306.4	433.7	550.8

[a] The calculation is based on literature experimental data (Richard J. Harper et al., 2014)

The data in Table 4-3 show the clear differences in biomass productivities with slope positions when 4000 stems per ha were planted. The most biomass productivity at lower slopes was 1.1-2.5 times higher than the one at upper slopes. When compared to *E.occidentalis*, double amounts of biomass were produced by *Pinus Radiata*.

3) The Ratio of Energy Outputs and Inputs

The net energy balance ratio of a biomass can be defined as the ratio of the energy intensity of the oven-dried biomass in trees to the non-renewable energy used in its production, i.e., energy output/energy input (Wu et al., 2008). The net energy balance ratio (R) in the PFT system heavily depends on the energy productivity on site. According to the results shown in Table 4-2, the energy ratio was range from 3.74 to 26.99 and the average of the ratio was 9.14.

The overall energy balance of PFT biomass production was better than other energy crops, e.g. rapeseed in WA (has an energy ratio of <7.0 with energy productivity ranging from 19.49 to 40 GJ/ha-year (Rustandi & Wu, 2010)). But, this energy balance was less than the biomass in WA when compare to the valley system in Wheatbelt (with an energy ratio of 41.7, energy productivity of 206 GJ/ha-yr (Wu et al., 2008)). Clearly, the energy ratio or biomass efficiency significantly depends on energy productivity.

4.4.2.2 Biomass energy footprint from the PFT system

In the last section, the energy ratio was analysed and the positive results encourage a further assessment of the energy footprint. The energy footprint indicates the energy required per 1 MJ biomass. The average biomass yield (19.0 dt/ha) was used in the energy footprint calculation. In this study, tree harvesting involves the use of heavy machinery to remove and chip entire tree components. With constant stem density, these energy inputs are assumed constant because the activities are the same regardless of weather, soil or land conditions.

From the aforementioned energy inputs and outputs, the energy footprint of the base-case biomass production is 25 kJ/MJ biomass, as shown in Figure 4-2. The harvesting stage alone contributes to 41% of the total energy input, followed by transportation (33%), and planting (14%), whereas site preparation and management only accounts for 12% of the total energy requirement.

When examining the individual energy input items, Table 4-2 shows that the energy input is the same for all sites which is 11,250 MJ/ha. The energy footprints range from 14 to 52 kJ/MJ biomass. It is found that the single largest contributor to the total energy input is fuel and oil, which together consume 19 kJ to produce 1 MJ biomass in the base scenario, equivalent to 69% of the total energy input. The major processes that consume fuel and oil are harvesting and biomass transportation. However, fertilisers were not applied on the PFT system but on alley system. The results will be discussed in section 4.5.

Based on several previous studies (H.Wu., 2008,; R.J.Harper, 2014), biomass productivities differ by more than 3.6 fold (9.2 to 33.5 dt /ha) in one farm based on differences in tree species and site conditions (R.J.Harper, 2014); this variation will be greater when broader areas are considered and climatic and other factors come into play (Roxburgh, 2004). The main reasons for differences in productivity are the soil water deficit (highly related to tree species), the slope of the landscape, water availability and regional effective rainfall.

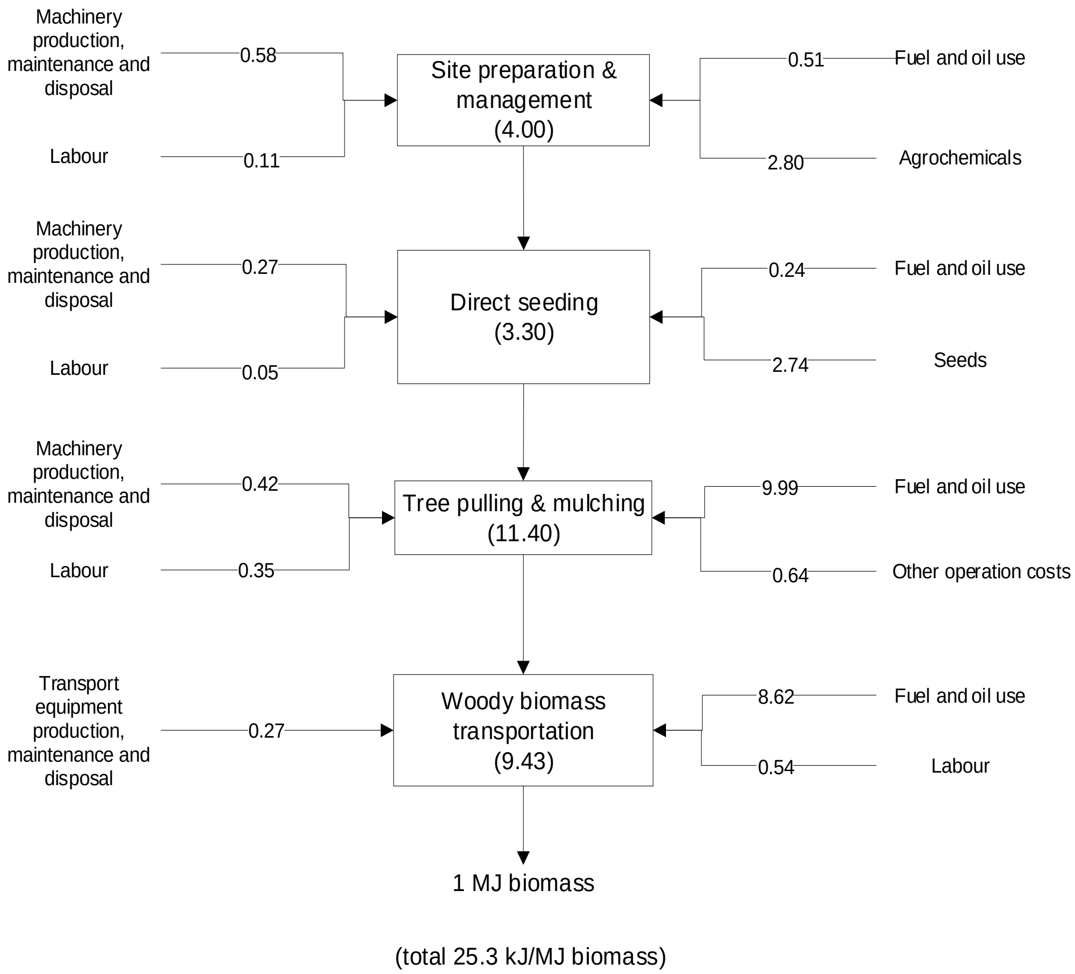

Figure 4-2: The energy footprint of biomass from the PFT system

4.4.3 Life cycle carbon impact of biomass from the PFT system

The life cycle carbon impact assessment evaluates the quantitative effects of GHG emissions from the PFT process. Similar to energy footprint, the carbon footprint in this study is assessed with same functional unit (i.e. MJ biomass), and the average biomass production is 19.0 dt/ha after 5 years growth interval in the PFT system (Richard J. Harper et al., 2014). In this study, the dynamic carbon sequestration in both above-ground biomass (i.e., wood, barks, twigs and leaves) and below-ground biomass (i.e. roots) is simulated. Furthermore, the impact of Land-use and Land-use change (LULUC) is analysed. The detailed approaches for assessing GHG emissions and impacts are described in the next sections

4.4.3.1 GHG emissions from Land Use and Land Use Change over the production period

During the life cycle of phase farm with trees production, carbon is dynamically sequestered in soils, above- and belowground biomass. The soil organic carbon (SOC) stock is an important figure that indicates the soil condition because the SOC stock decreases with increasing salinity and vice verse (Ritson et al., 2015). Furthermore, the extent of carbon sequestration in soils depends upon the plant decomposition of organic matters and soil condition. Therefore revegetation which aims at increasing the soil carbon stock is one of the strategies of salinity management.

The LCA in this study follows the IPCC good practise guideline, which includes land use and land-use changes, forests, and farming activities such as afforestation, reforestation and deforestation. Carbon emission is calculated based on annual biomass changes. This comprises an annual change in carbon stocks in above- and below-ground biomass, the annual change in carbon stocks in dead organic matter and annual change in carbon stock in soils. The FullCAM model, which was developed by the Australian Department of the Environment, has been employed to determine the carbon emission in this study (Department of the Environment and energy, 2013). This model provides enormous forestry and agriculture spatial data, the plant species growth data and spatial weather data (Department of the Environment and energy, 2012). This study simulated a total of 14 years native plants and crops production period from 2016 to the end of 2030 by employing the FullCAM model with field data.

The abandoned scald lands are infertile, saline and eroded. Since there lands have lost the organic matter, the carbon flux is ignored in this study, and thus the initial baseline was set as zero (IPCC, 2006).

The carbon sequestrations in above- and blow-ground biomass and soil were simulated. There were three important findings which have been illustrated in Figure 4-3. First, the SOC increased from 0.00 to 0.59 tonne C/ha (0-30 cm) during the 4 years tree phase, then the soil carbon increased from 0.59 to 1.32 tonne C/ha over the 10 years crop phase. The harvesting of trees did not affect the soil carbon, however, during the crops growing stage, the soil carbon increased by 14%. After harvesting, the soil carbon expectedly decreased by 2%. The Figure 4-3 has also shown that the SOC increased by 55% over 10 years during the crop phase but SOC increased by 59% over 4 years during the tree phase. This can be explained by land use change effects. SOC decreases from native forest to crops and increases from crops to native forests (Guo & Gifford, 2002). In addition, rates of SOC can increase or decrease depending on the cropping system, climate and landscape hydrology. The lack of suitably detailed soil attributes and cultivation age maps makes the analysis of Land use SOC rather difficult.

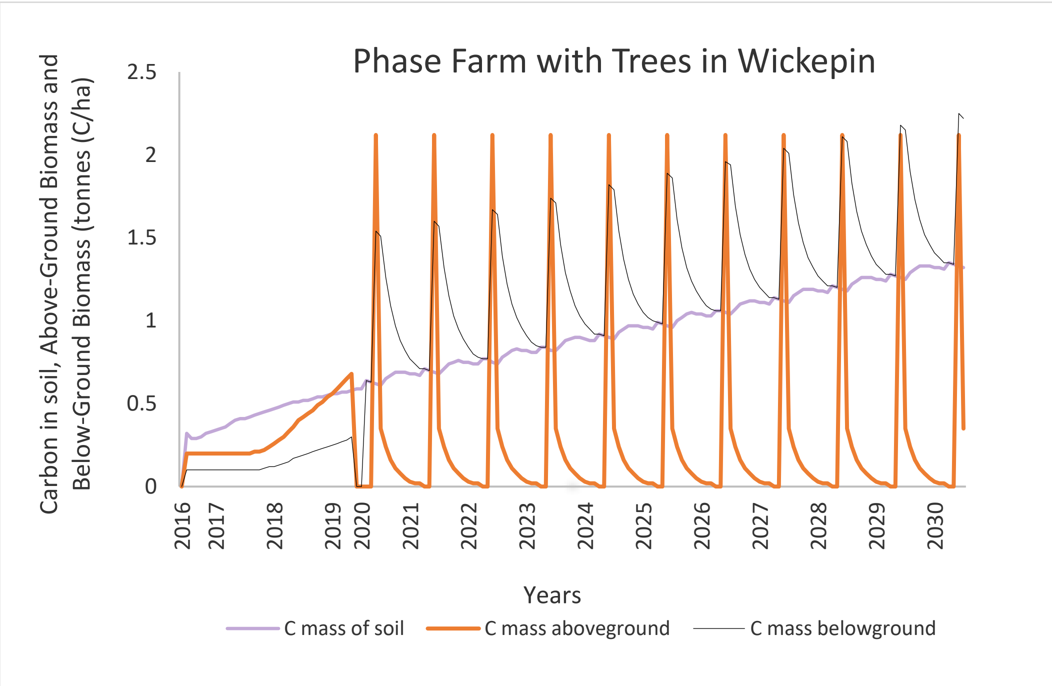

Figure 4-3: Dynamic changes of carbon in soils, above- and belowground biomass over a 14 years production period in PFT and agriculture system

4.4.3.2 GHG emissions from Land Use and Land Use Change Forest over the growth period

The carbon sequestrations to plants and carbon mass in soil were simulated. There were three important findings which have been illustrated in Figure 4-4. First, the soil organic carbon (SOC) increased from 0.00 to 1.82 kg C/ha (0-30 cm) during the 5 years tree phase when it is an average 19.0 dt/ha productivity. The above- and below-gournd biomass were harvested, the soil organic carbon came from fine roots, dead organic matter and debrits from the trees during the growing period. Figure 4-4 has shown that the SOC increased by 18 % over 5 years during the tree phase, this can be explained by the land use change effects. In addition, the rates of SOC can increase or decrease depending on the cropping system, productivity, climate and landscape hydrology.

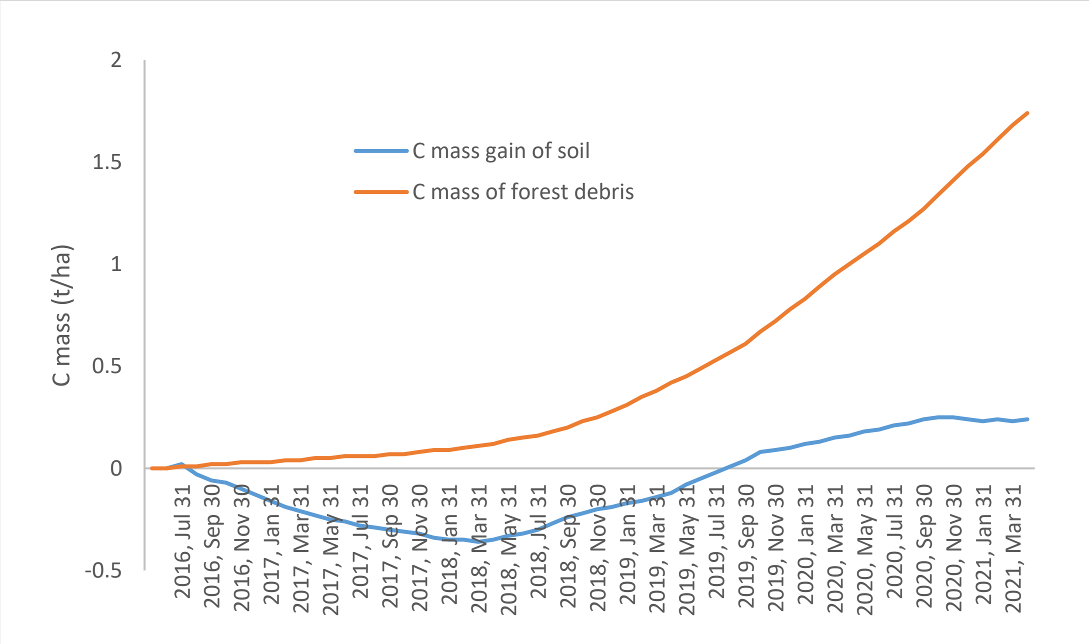

Figure 4-4: Dynamic changes of carbon mass in soil and forest debris over a 5 years production period in the PFT system

4.4.3.3 Carbon footprint of biomass produced from the PFT system

Figure 4-5 has shown that total life cycle GHG emissions during biomass from PFT system follow similar trends to total life cycle energy inputs. The total GHG emissions during the reforestation phase are 3.05 of g CO_2-e/MJ biomass. The contributions of these activities to the total GHG emissions follow the order of woody biomass transportation (47%) > harvesting (26%) > site preparation and management (16%) > planting (11%).

Moreover, the soil may sequester additional carbon depending on the balance between the addition and decomposition of organic material in the soil (Y. Yu, 2015). The carbon mass from fine roots and organic matter was measured 26 years after reforestation at two sites in the Western Australia wheatbelt (R. J. Harper, 2012). with no significant differences of soil organic carbon stores between reforested sites and adjacent farmland.

Besides the GHG emissions from farming activities, carbon is also dynamically sequestered in both above- and belowground biomass due to land use change. Moreover, the soil may sequester additional carbon depending on the balance between the decomposition of organic materials in the soil.(Yu et al., 2015)

The detailed soil carbon assessment was conducted in the last section where the soil organic carbon in this study is 1.82 kg C/ha over the 5 years. Here, the above- and below-ground biomass is assume to be eventually combusted for energy recovery, the carbon sequestrated into which will be released to atmosphere again. Therefore, the carbon sequestrated into biomass is not considered in determining the carbon footprint for biomass production. For this perspective, the SOC gain is more important in determining the overall GHG emissions from biomass production via the PFT system. Although the overall carbon footprint from PFT system indicates that carbon sequestrated into the soil is less than 0.3% of the total GHG emission from activities. This finding encourages the stakeholders and researchers to take land-use change into account because of scaled land are corrected.

4.4.3.4 Variations of Energy and Carbon Footprints with Biomass Productivity

Based on several previous studies (Richard J. Harper, 2014; Richard J. Harper et al., 2014; Wu et al., 2008), biomass productivities differ by more than 3.6 fold (9.2 to 33.5 dt /ha) in one farm based on differences in tree species and site conditions. The main reason was the soil water deficit, and water deficit is highly related to tree species, the slopes of the landscape, soil condition, water availability, regional effective rainfall and irrigation frequency.

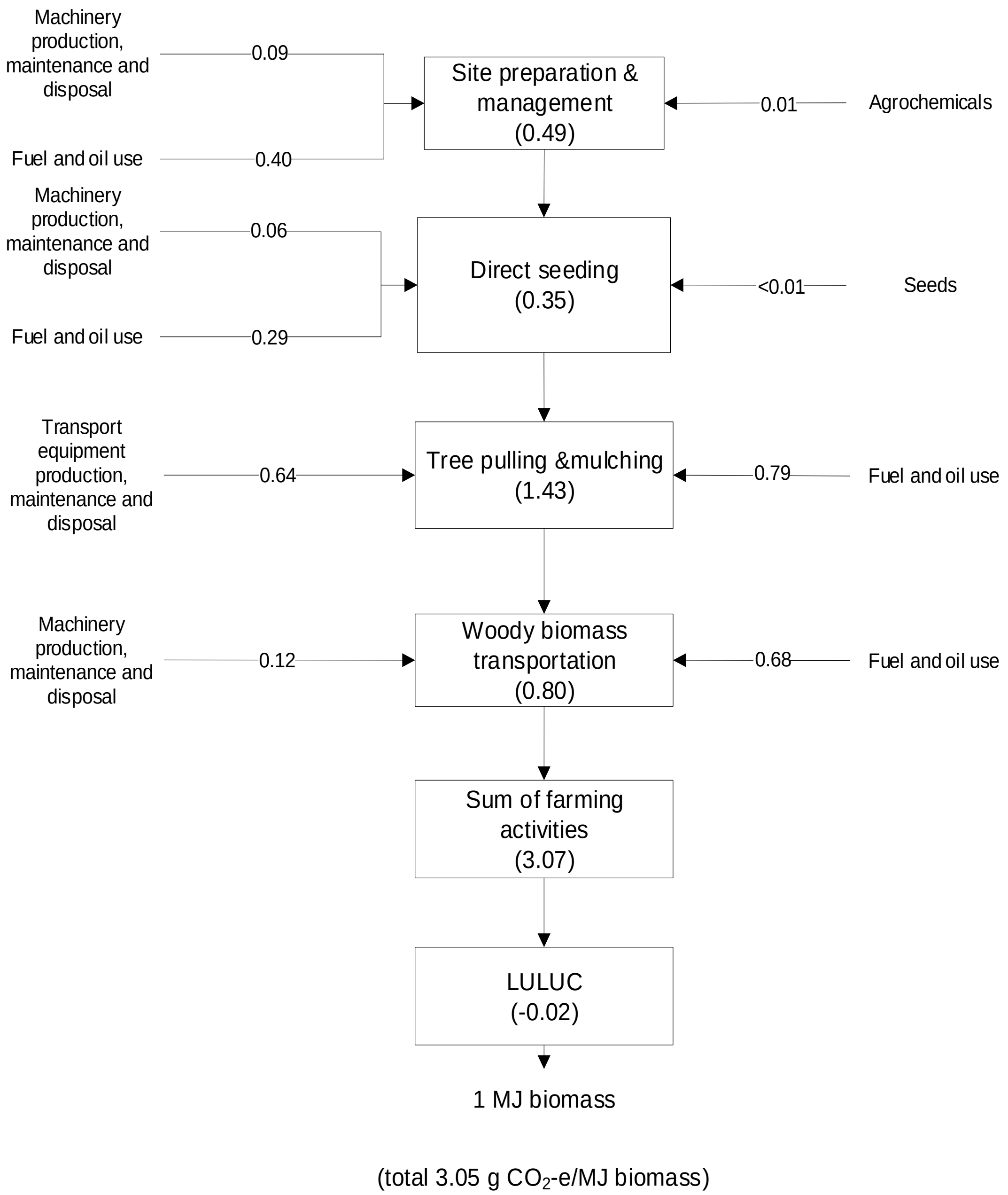

Figure 4-5: The carbon footprint of biomass production from the PFT system (the unit for all the numbers is g CO_2-e/MJ biomass)

In this study, tree harvesting involves the use of heavy machinery to remove and chip entire tree components. With constant stem density, these energy inputs are assumed constant because the activities are the same regardless of weather, soil or land conditions. Those results are proportional to the productivities. However, as shown in Table 4-4, the carbon footprints are 6.32, 3.05 and 1.72 g CO_2-e/MJ biomass for low, base and high case respectively.

Table 4-4: Energy and carbon footprints via biomass productivity

	Low case (9.2 dt/ha)	Base case (19.0 dt/ha)	High case (33.5 dt/ha)
Energy inputs (MJ/ha)			
Site preparation and management		1,319	
Planting		1,600	
Harvesting (tree pulling & mulching)		4,560	
Woody biomass transportation		3,771	
Total		11,250	
Carbon emission of farming activity			
Carbon emission (($g\ CO_2$-e/ha)[a]		1.23	
LULUC			
Carbon in soil ($g\ CO_2$-e/MJ) [b]		0.02	
Energy outputs			
Productivity (MJ/ha) [c]	193,660	399,950	705,175
Footprints			
Energy footprint (kJ/MJ)	52	25	14
Carbon footprint ($g\ CO_2$-e/MJ)	6.32	3.05	1.72

[a] This carbon emission of farming activities was simulated with GREET model.
[b] Carbon is from fine roots, above- and below- ground debris.
[c] Include above- and below-ground biomass.

Carbon footprint is a complex, especially the soil carbon assessment that because of the carbon movements and large quantities of the samples will be required in order to produce the accurate the results. Therefore, if carbon footprint includes LULUCF sector, it should be assessed and interpreted on case-by-case bases. Alternatively, carbon mass in LULUCF sector can be assessed alone.

4.4.4 Life cycle water impact of biomass from PFT system

4.4.4.1 Water requirements during PFT farming stage

It is widely accepted that Australia is the driest continent in the world, where the issue of water scarcity was noted in the early nineteen centuries. The Australian government has spent decades to investigate and manage the best irrigation system through efficient utilization of underground water. The effectiveness of irrigation and utilisation of water resources were well established in the early 1990s. The blue water footprint is only less than 1% of the total water footprint. This is also confirmed by the Australian Bureau of Statistic and Water Corporation Survey (National Water Commission, 2005) and verified by data from the Bureau of Meteorological Data.

There is no single complete method to compute the green and blue water footprints; i.e., no single data set to calculate the water footprint. In this study, more work is focused on the relationship between soil water, the landscape and the efficiency of water use. In Australia, very little study has been done on effective irrigation for various lands conditions. For a long term management of abandoned scald land, it is essential to carefully design the replanting of native forest, in order to achieve success. For this study, the rainwater, evapotranspiration and weather data were based on government publications (Bureau of Meteorology, 2014a).

Blue water footprint ($WF_{(b)}$) refers to the consumption of blue water resources. Blue water comes mainly from rainfall, and the data from Bureau of Meteorology shows that blue water is far insufficient for any plants to survive in Australia. The main water source for agriculture is green water (WF_g), which is from rivers or underground, such as the irrigation system.

Biomass productivity is the key indicator that should be considered to evaluate the WF_g in relation to energy performance. In this study, the quantities of biomass production were based on several experiments and literature research (Richard J. Harper, 2014; Richard J. Harper et al., 2014; Wu et al., 2008). We found that the quantities of production differ by more than three folds at different regions and landscapes. The main reason was the soil water deficit, and water deficit is highly related to tree species, the slopes of the landscape, soil condition, water availability, regional effective rainfall and irrigation frequency. The site experiments from Murdoch University have shown that the biomass productivity from the common native tree species ranges from 329 GJ/ha to 1027 GJ/ha in Western Australia. The maximum water deficit ranges from 0.04 to 0.13 kL/GJ.

Table 4-5 has shown that higher biomass productivity has imparted lower water footprint. This is because plants consume the same quantity of water in one particular area. The higher density plantation will definitely achieve higher productivity with low water consumption. This is because high density plantation can easily achieve close canopy, which will result in better soil water storage. Nonetheless, four times the density of trees doubles the soil water deficit from the bottom to the top of the slope. Hence, 4000 stem plantation leads to 0.04 kL/GJ water deficit with 1027 GJ/ha productivity, but 1000 stems plantation leads to 0.21 kL/GJ water deficit with only 329 GJ/ha productivity.

Table 4-5: Soil water deficits via biomass productivity

	Biomass Productivity (GJ/ha)				**Soil water deficit (kL/GJ)**			
Growth duration	Year 3		Year 4		Year 3		Year 4	
Density (trees/ha)	1000	4000	1000	4000	1000	4000	1000	4000
E.globulus	460	696	636	871	0.13	0.07	0.09	0.06
E.occidentalis	398	819	548	990	0.12	0.08	0.08	0.07
P.radiata	329	724	560	1027	0.21	0.06	0.09	0.04

* Calculated from Harper's data

4.4.4.2 Landscape effect of green water footprint

Table 4-6 has shown the amount of water use by trees that do not always depend upon their position in the landscape. The trees on the top of slopes utilised more water than those at the bottom of the slopes. When the tree distribution is less dense, such as 1000 stems per hectare, the soil water deficit is only slightly increased from the bottom of about 3 mm/GJ-ha-yr to the top of about 14 mm/GJ-ha-yr of the slope. This table has also shown that the best tree density for planting *Eucalyptus occidentalis, Pinus radiate* and *Eucalyptus globulus* should be 4000 stems per hectare because of the lowest WF_g achieved. There are very few studies on water footprint that have been conducted for Australian native plantations. No many data or literature can be found on the strategies for native trees plantation to achieve the best biomass productivity.

Nevertheless, the soil water deficit is strongly related to the slope position of the landscape. Trees on the hill need about 3 times more water than those in the valley, and the biomass production is 4 times higher at the valley than that on the upper slope. This has led to the water footprint for the forest on the upper slope as high as 0.13 kL/GJ, whereas the water footprint for the forest at the valley was only 0.04 kL/GJ.

The tree growth phenomenon can be explained by the architecture of the root system. According to Yoav and co-workers, the trees on upper-slope side will be held in tension, where they anchor the sliding mass to the stable side to prevent further movement from shared stress. It is possible for the roots to grow deep to reinforce the soil but the strength of the anchorage depends on the steepness of the slopes (Waisel, Eshel, & Kafkafi, 2005). If the trees on top of the hills bear the wind load consistently, the trees will require longer and thicker roots for reinforcing the soil strength. Ultimately, the roots will grow thicker and longer on the windward side than the remaining roots, if the wind load comes from only one direction all year round (Gartner, 1995).

Table 4-6: Soil water deficits at different positions relative to water footprint from biomass [a]

	soil water deficit (mm/GJ-ha-yr)				Biomass (GJ/ha)			
Growth duration	Year 3		Year 4		Year 3		Year 4	
Density (trees/ha)	1000	4000	1000	4000	1000	4000	1000	4000
upper-slope	14	8	11	8	185	665	306	842
mid-slope	6	5	5	6	298	689	462	744
lower-slope	4	3	3	3	704	884	976	1303
average	8	6	7	6	396	746	581	963

[a] Estimated from the unpublished data of Harper R. J. (Richard J. Harper, 2014)

4.4.4.3 Effects of plantation density on green water footprint

Maximising the usage of lands is the ultimate goal of biomass plantation while improving the soil quality. Table 4-6 has also shown that trees in the high density plantation require less water. At the upper-slope land, the WF of 1000 stems plantation was higher (i.e. 0.13 kL/GJ) than that of 4000 stems plantation (i.e. 0.06 kL/GJ). At the lower-slope land, the WF of 1000 stems plantation was slightly higher (i.e. 14 kL/GJ) than that of 4000 stems plantation (i.e. 11 kL/GJ). These values are representative only for 3 years rotation. In this case of 5 years rotation, these values are 10 and 8 kL/GJ respectively.

It is interesting to note that WF affects the tree density of plantations at different land slopes. At a particular location, a high soil water deficit will lead to high water consumption as well as high WF. Ultimately, when the soil moisture is sufficient for tree roots, the WF was only 8 kL/GJ. This phenomenon has been widely studied in the scientific communities in order to utilizing water efficiently.

The estimated water footprint of biomass represent the volume of water that is allocated to green biomass and that approximately green biomass contains 45% moisture. It will be great option to reuse water if the water from green biomass is recycled from drying process before feed into pyrolysis reactor.

4.5 Benchmarking on footprints of various biomass production

As mentioned in Section 2.1.1.2, the tree belts strategy has been developed in Wheatbelt areas where this is also named as the tree valley system has been studied over 12,000 ha since the activities were carried out (Yu et al., 2015). Yu and co-workers concluded that low carbon footprint is achievable even if the soil is unfertilised, although the fertilising needs to be considered in the life cycle analysis. Nevertheless, the disadvantage of tree belts is displacement of food production in water-limited environment and also competition between the trees and adjacent crops due to the large tree roots area. Harper et al. have proposed the phase farm system (PFT) that plant native trees in scald land for four years and then plant crops for ten years (Richard J. Harper et al., 2014; Sochacki et al., 2012).

Table 4-7: A comparison of life cycle energy and carbon footprints with biomass grown between PFT system and valley system

	PFT system	Valley system
Landscape suitability	Non-saline recharge areas	Non-saline recharge areas
Advantages	Reduction of competitive effects for water with crops. Potential to get watershed wide removal of excess water, nutrients	Providing shelter, compatibility with cropping, utilizing surplus water across recharge areas
Disadvantages	Removal of roots	Competition of water between the trees and adjacent crops, woody species need to be compatible to the adjacent agriculture crops
Production duration	5 years	50 years (Wu et al., 2008), 67 years(Yu et al., 2015)
Plant species	*Eucalyptus globulus, Eucalyptus occidentalis*, *Pinus radiate*	*Eucalyptus mallee*
Harvest consideration	Above- and below- ground biomass	Above-ground biomass only
Productivities (dt/ha-year)	1.8 – 6.7 [a]	9.8 (Wu et al., 2008), 3.9 – 15.4 (Yu et al., 2015) [b]
Energy input (GJ/ha-year)	2.3 [c]	4.95 (Wu et al., 2008), 4.46 – 6.7 (Yu et al., 2015) [d]
Energy footprint (kJ/MJ biomass)	14 - 52	14.3 – 34.8 (Yu et al., 2015)
Carbon footprint (g CO_2-e/MJ biomass)	6.34, 3.07, 1.74	-14.5[e], 3.1[f] (Yu et al., 2015)

[a] The biomass yield depended on landscape, soil conditions and plant species.
[b] The biomass yield depended on fertiliser application (Yu et al., 2015).
[c] Assume energy inputs with 4000 stem/ha at different site experiments.
[d] Energy inputs depended on the fertiliser application at different site.
[e] Considering carbon sequestrations because of below-ground biomass and land-use change.(Yu et al., 2015)
[f] Without considering the carbon sequestrations because of below-ground biomass and land-use change.(Yu et al., 2015)

Table 4-7 presents the key energy and carbon footprints of alleys of trees interspersed with cereal cropping and the PFT system, which leads to two interesting findings. First, due to the differences of annual biomass productivities (1.8 – 6.7 dt/ha-year for the PFT system and 3.9 − 15.4 dt/ha-year for the alley system), the energy footprints of the PFT system range from 14 to 52 kJ/MJ biomass, which are slightly higher than those of the alley system (14 − 22 kJ/MJ biomass). The PFT system did not apply fertiliser but valley system did and fertilisers was counted of one of the energy inputs. The alley system harvested yearly after 3 to 5 years initial reforest stage, but the PFT system harvest only once after 5 years initial reforest stage. Second, the carbon footprints of the PFT system range from 1.72 to 6.32 g CO_2-e/MJ biomass, in comparison with those of -14.5 − 3.1 g CO_2-e/MJ biomass for the alley system. The range of carbon footprints of the alley system is wider than that of the PFT system, which is a response to the differences in biomass productivities which is most likely due to being drawn from a greater range of planting environments than the PFT experiment, which was on one site. Overall, the environmental burdens (energy and carbon footprints) of biomass production from the PFT system are similar to those for the alley system. However, the choice between these two tree farming systems depends primarily on the nature of the local hydrological and geological systems, and the likely economics, taking into account the loss of foregone cereal production and any environmental payments for restoring landscape hydrology.

4.6 Conclusions

A LCA has been conducted to evaluate the energy, carbon and water footprints of biomass production from the PFT system in abandoned scald farmlands in Western Australia.

This study has determined fuel and oil as the single largest contributor to the total energy requirement. It has highlighted the important role of soil conditions and land-use change in determining the carbon and water footprints of biomass production from PFT system. This study has also analysed the water footprint. The water footprint is strongly related to landscapes and tree density plantations. In summary:

- Both fuel and oil consume 30 kJ for producing 1 MJ biomass and that is 38% of the total energy requirement.
- The total primary energy requirement is 22.5 GJ/ha. The crop establishment consumed 29% of the total primary energy requirement, which is contributed by the use of fertilisers.
- The GHG emission from farming activities and soil organic carbon sequestration are 1.23 and 0.02 gCO_2-e/MJ biomass respectively. The positive energy ratio (i.e. average 9.14) and small energy footprint (i.e. which are in the range of 14 – 52 kJ/MJ biomass) will help to encourage the biomass production in WA.
- The overall GHG emission of biomass production from the PFT system is 3.07 g CO_2-e/MJ biomass (base-case scenario). The carbon sequestration in soils can be doubled if the productivity is high. Thus, the negative carbon footprint can be achieved if the land is used correctly.
- The comparison of life cycle energy and carbon footprints to biomass production between PFT system and tree valley system has shown the disadvantages and advantages of both. The choice between the PFT system and the tree valley system depends on the nature of the local hydrological and geological system.
- The 4000 stems plantation has led to 0.04 kL/GJ biomass water deficit with 1027 GJ biomass/ha productivity, but the 1000 stems plantation has led to 0.21 kL/GJ biomass water deficit with only 329 GJ biomass/ha productivity.
- In terms of the plant position of the slope of the landscape, this study has found that the biomass production is 4 times higher at the valley than that on the upper slope. Hence, trees on the hill need about 3 times more water (i.e. 0.13 kL/GJ biomass) than those trees in the valley (i.e. 0.04 kL/GJ biomass).

Therefore, land-use change and tree density of the plantation are the key factors to reduce the energy, carbon and water footprints of biomass productivities in Western Australia.

Chapter 5 Biodiesel – BMG blend process

5.1 Introduction

Biodiesel is one of the future fuel options in the market because it is clear that utilising waste cooking oil helps to solve environmental problems associated with the disposal of waste cooking oil (Jiang & Zhang, 2016; Morais et al., 2010; Patil et al., 2012; Sheinbaum-Pardo, Calderón-Irazoque, & Ramírez-Suárez, 2013; H. Zhang et al., 2012). Western Australia produces approximately 50 million litres of waste cooking oil (WCO) per year (A. Wright, 2007). Using WCO as feedstock for biodiesel production not only reduces costs but also addresses the waste recycling environmental impact (Chua et al., 2010; Morais et al., 2010). Biodiesel transesterification process is the most common technology of biodiesel process (Morais et al., 2010). Nevertheless, crude glycerol is the by-product from biodiesel process and it has become an issue due to limited market demanding.

In this study, biodiesel from WCO process involves WCO collection and transporting it to a bio-refinery plant. The final product is biodiesel and the by-product is glycerol. This biodiesel from WCO process was described in Chapter 2. Transportation cost is the feedstock cost of biodiesel process, and it may limit the biodiesel development because of Perth's very low population density (Australian Bureau of Statistics, 2011; Jiang & Zhang, 2016). An effective system of WCO collection logistics depends on the landscape and local road traffic conditions (Ling, Duan, Zhang, & Zhu, 2013). Hitherto, there are insufficient reliable evidences to indicate where most of WCO is generated in Western Australia, and the efficiency of WCO transport in this biodiesel process is also unknown. In addition, the best bio-refinery plant location is also needed to be determined as part of transportation analysis.

Parallel to biodiesel process, bio-oil is an alternative fuel from lignocellulosic biomass pyrolysis process. It has caught researcher's attention since it is a widely available and cheap organic material. The process chain of biomass production from forest plantation and agricultural biomass waste was gained attention in last decades. Most research has taken into consideration from seeds to tree biomass harvesting, the raw material, chemicals, fertilisers, water, labour, energy, land use change and the farm machinery.

Chapter 4 investigated biomass from the PFT system and found the significance of biomass production while reversing the condition of dry salinized land. In this study, mallee biomass is planted on sanitised abandoned farmland as one of the salinity management strategies. The first stage was agro-forest production, where forest trees were planted for 5 years and harvested above- and below- ground biomass. Thereafter, the land was used for crops for 10 years, so the entire period was 15 years. From seeds to tree biomass harvesting, the raw material, chemicals, fertilisers, water, labour, energy, land use changed and the machineries were all taking into consideration. The agriculture stage only considered the agricultural waste collection. The second stage was for biomass preparation prior to the pyrolysis reaction, where parameters of heat energy, labour and transport were considered. The third stage was pyrolysis reaction, where bio-oil is the main product of pyrolysis process and biochar was a by-product of the production process. In this stage, the process heat, reaction vessels, chemicals, plant operation energy, labour and land were all considered. The product bio-oil also needs to be distributed to the filling stations, where 65% of the by-product biochar was recycled to heating pyrolysis vessel and the remaining biochar was thrown back to the land as fertiliser.

The biomass then undergoes pyrolysis reaction to produce bio-oil, even though bio-oil development suffers from its bulk, fibrous nature (Yu & Wu, 2010), and that low market demand for the by-product glycerol is an issue for all biodiesel refineries. Mingming Zhang and co-workers have investigated blending the bio-oil, crude glycerol and methanol as emulsified fuels (M. Zhang, 2015a, 2015b; M. Zhang & Wu, 2014). The effect of impurity, ageing stability and fuel solubility of this new type of fuel was examined in depth by these researchers (M. Zhang, 2015a; M. Zhang & Wu, 2014). The findings provided an attractive strategy for utilising crude glycerol and bio-oil. The advantages of the BMG blend fuel are many which include (a) utilising crude glycerol and crude bio-oil, (b) utilising the methanol from crude glycerol after the biodiesel separation process, and (c) less waste going to the landfill from the process. However, the value of this BMG fuel is still unknown.

It is important to evaluate the value of the new fuel and new economics of the process performance. Firstly, it provides sufficient evidence to design the new process or simplify the existing biodiesel process, i.e., eliminate methanol recycling from glycerol process or alter the glycerol separation process into blending process. Secondly, it provides the market confidence by virtue of production cost reduction and higher credit from by-product. Thirdly, if the new process improves the economics significantly, it can even lead to booming of biofuel worldwide as a triple-win new business opportunity.

Therefore, in this chapter, Section 5.4 analyses the transportation impact of biodiesel-BMG blend process to serve the first and second objectives in Section 2.3. The transportation in this process involves; (a) survey of quantifying WCO in Western Australia, and (b) determine the best route of collecting WCO, tortuosity and bio-refinery plant location. Section 5.5 aims to develop a new process by combining biodiesel and bio-oil processes to produce high purity biodiesel and bio-oil/methanol/glycerol (BMG) blend, where no glycerol purification or methanol purification is required in this new process. This new fuel is produced and the price of the new fuel is predicted in this chapter. Section 5.9 assesses the energy and carbon footprints over the entire biodiesel process.

5.2 Boundary of the biodiesel-BMG blend production process

This study modifies the original biomass production from the PFT system by assuming that a fraction of biomass is separated from average 19.0 dt/ha biomass production process. Only less than 5% of biomass is used for the bio-oil process and blending process. In this study, all the farm activities are included in life cycle energy and carbon assessment, irrespective of whether indirect energy or direct energy is consumed in the activities. The land use and land use change are included in the life cycle carbon assessment. However, the impacts of facility construction and capital equipment are excluded in life cycle energy and carbon assessments, as these impacts are typically negligible when allocated over the total quantity of product manufactured over the life cycle of the facilities and equipment (International, 2010).

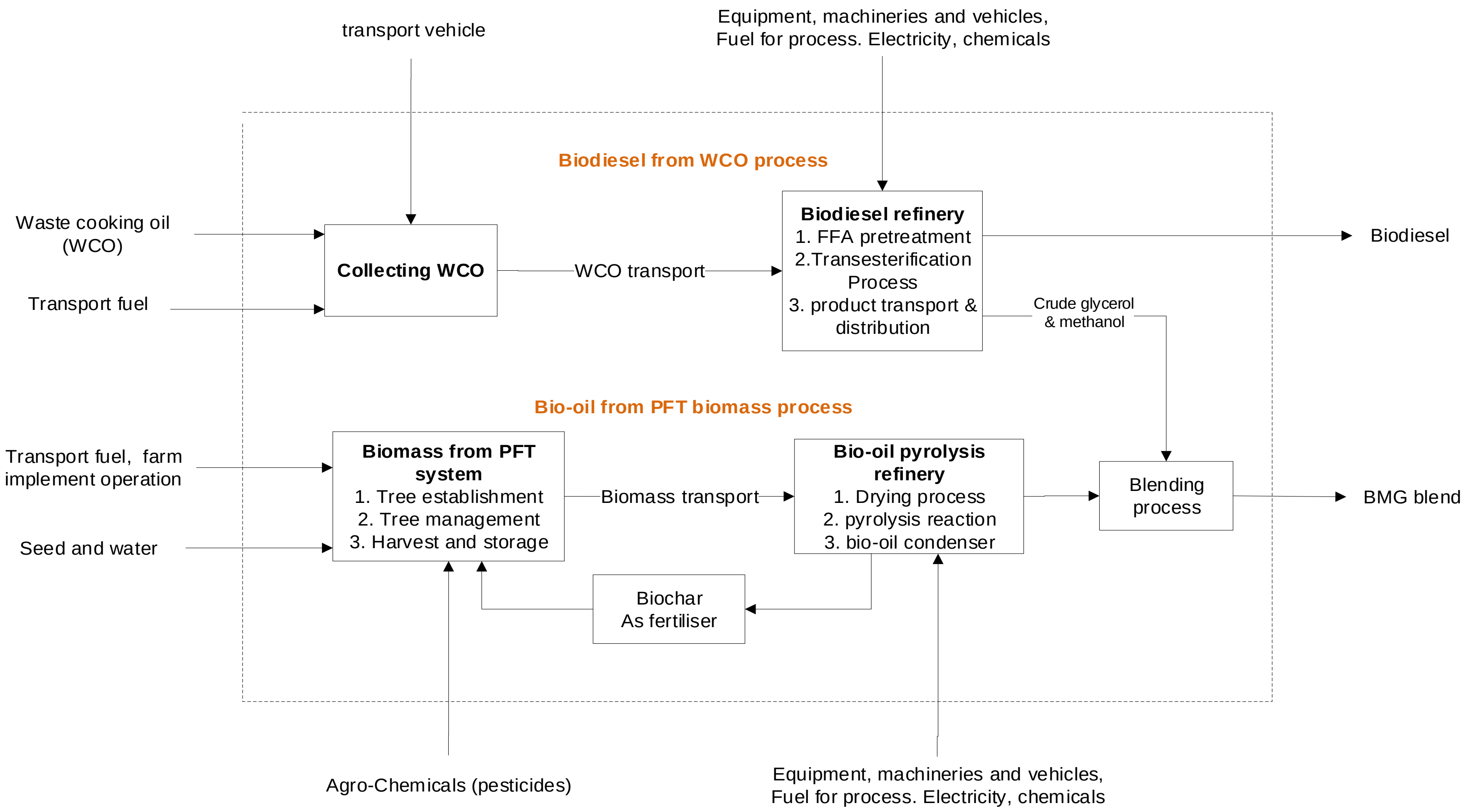

Figure 5-1: The system boundary of biodiesel-BMG blend production process

Figure 5-1 has shown an overall description of the biofuels process that produces biodiesel biochar and BMG blend from mallee tree seeds and waste cooking oil from an urban area in Perth. Biomass was produced from the phase farming with tree system (PFT) system, as was described in Chapter 4. The biomass is harvested and transported to the bio-refinery plant, followed by fast pyrolysis reaction to produce bio-oil. Both bio-oil and biochar are the products of the fast pyrolysis reaction. In this study, it is assumed that the heat for the pyrolysis reaction and drying process is provided by a fraction of pyrolysis biochar, which is 30.15 MJ/kg (Gheorghe, Marculescu, Badea, Dinca, & Apostol, 2009). Parallel to bio-oil from the biomass process, biodiesel was produced from waste cooking oil that was collected daily in an urban area. Then the by-product crude glycerol is blended with bio-oil and extra methanol to form the final product – BMG blend. Biodiesel with purity >98% was achieved from this simulation, and it is assumed to be used as transportation fuel. Biochar is thrown back to the biomass farm land as fertiliser.

The economic assessment of biofuel process is carried out at the end of this chapter, and the price of BMG blend is predicted by the correlation between high heating value (HHV) and the fuel prices. The economic analysis uses a combination of Aspen Process Economic Analyser for equipment cost and Holger Nickish economic analyser spreadsheet calculation. The results are discussed in Section 5.10.3.

5.3 Survey of Western Australia waste cooking oil

This survey was designed specifically to quantify the waste cooking oil resources that were generated from restaurants and fast food chains in Perth metropolitan areas. The survey was conducted over a period of several months. The business groups are five-star restaurants, fast food chains, cafes, fish & chips shops and private canteens. The data from these businesses indicate WCO's rate of throughput and flow directions. This survey captured as many facts of WCO handling as possible. These ranged from the volume of waste oil generated in a week, waste cooking oil disposal and local industrial or government engagements. The survey data was broken up into four categories according to the type of restaurants for a more thorough analysis of WCO profile. Table 5-1 illustrates the full information of WCO quantities in Perth metropolitan areas.

Table 5-1**:** Survey of quantity of WCO in Perth Metropolitan area

Business type	Total population	Average WCO generated (kL/month)[a]	Projected WCO generated (ML/year)
Five star Restaurants	51[b]	0.68	0.104
Fish & chips shops	170[b]	0.47	0.056
Fast food stores	1254[c]	21.42	25.786
Canteen Café Bar	1062[b]	18.51	22.253
Unspecified Restaurants	175	0.02	0.002
Total	2712[d]	327	48.201

[a] data from surveyed restaurants,
[b] data adapted from the website ("Urbanspoon Perth," 2012)
[c] fast food outlet data was adapted from the website (Markey & Watson, 2011), the data of contribution to the state in Australia from ABS (Australian Bureau of Statistics, 2013a)
[d] data was adapted from ABS in 2019 (Austrlian Bureau of Statistics, 2019), in 2012 the exit rate of businesses is 14.1%, the entry rate is 11.2% (Australian Bureau of Statisitics, 2013).

The information revealed the annual projected waste cooking oil throughout the Perth metropolitan area was 48.2 ML in 2024. The survey information also showed the overall quantity of feedstock needed for a biodiesel production initiative. However, taken into account the population growth of between 4.4 to 6.6 million by 2101 from the current population of 1.9 million (Australian Bureau of Statistics, 2013b). Therefore, in 32 years of production time, the growth range of WCO is expected to be somewhere between 55 ML to 84 ML.

To maximise the productivity while minimising the transport cost, a carefully designed WCO collecting route within the Perth metropolitan area is necessary. Zhang et al. (H. Zhang et al., 2012) mentioned that WCO is scattered in production points (restaurants, hotels, households, etc) and its collection problem may be an important bottleneck that limits its development. A professional recycling logistics system of WCO especially the design for door-to-door collection service and recycling facilities may help to solve this problem. This logistics system is simulated and discussed in the following subsections.

5.4 Transportation assessments

5.4.1 Best route of WCO collection

Minimizing the travelling distance is a must for not only minimizing the cost of the feedstock but also minimizing the greenhouse gas emissions from the collecting vehicles. Planning the best route of WCO collection is by minimizing the driving distance while maximizing the number of restaurant visits. The best route simulation was done by Matlab simulator, and the method was described in Section 3.3.2. The results are shown in Figure 5-2.

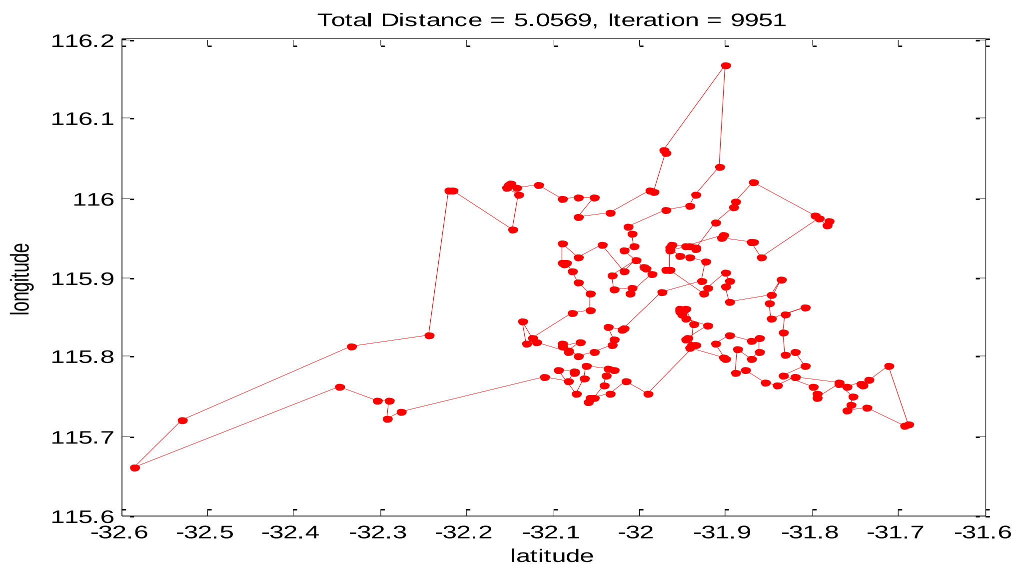

Figure 5-2: Route of collecting WCO from restaurants in the Perth metropolitan area

After 9951 iterations, on the earth surface, the shortest distance for WCO collection is 345 km. However, this is a straight-line distance from one latitude/longitude point to another latitude/longitude point. The real distance is multiplied by a tortuosity factor. The tortuosity factor is calculated and the details are shown in Section 5.4.3.

5.4.2 Bio-refinery plant location optimisation

The optimum bio-refinery plant location is one where the plant profit exceeds over investment. The best location would associate with the minimum production cost. It provides a quantitative measure for comparing the capital required for competing products and process in the current terms (Seider, Seader, Lewin, & Widagdo, 2009). The effectiveness of production costs are dependent on fixed costs, variable costs and capital dependent costs(Seider et al., 2009). Depreciation was calculated by the subtracting the salvage value from the total capital investment and then dividing it by life time of the refinery plant (Aspentech, 2016; Seider et al., 2009). In this study, the expected life time of the refinery plant is 30 years. Variable costs include raw materials, utilities, transport costs, other admin expenses and management incentives(Seider et al., 2009). Fixed costs included operation costs, maintenance, insurance and taxes (Aspentech, 2016).

5.4.2.1 Regional optimisation

This section shows the proposed optimal bio-refinery plant location in WA according to the economic criteria defined in the mathematic model. First of all, the sub-model was employed in order to determine the three category location options: (i) Perth CBD centre: The land located outside the metropolitan Perth (ii) abandoned bushland: Close to inner land in WA. Most abandoned bushlands are in the desert where there are no facilities and infrastructures; and (iii) Towns in WA: Towns in WA with already built government facilities and infrastructures.

In Australia, if a refinery plant is located in an abandoned bushland, the capital costs for roads and airport infrastructure have to be considered. In this study, the infrastructure costs are set at $130 million for building roads and airport for transportations (Topp, Soames, Parham, & Bloch, 2008). To make biofuels compatible in the market, the selling price should be lower than fossil fuels, therefore, the new fuel selling price is predictable. Our survey has shown that the WCO has generated 39 ML annually; hence the production rate and price were fixed due to the limitations of the feedstock. Therefore, reducing the costs is the only way to make the bio-refinery plant profitable.

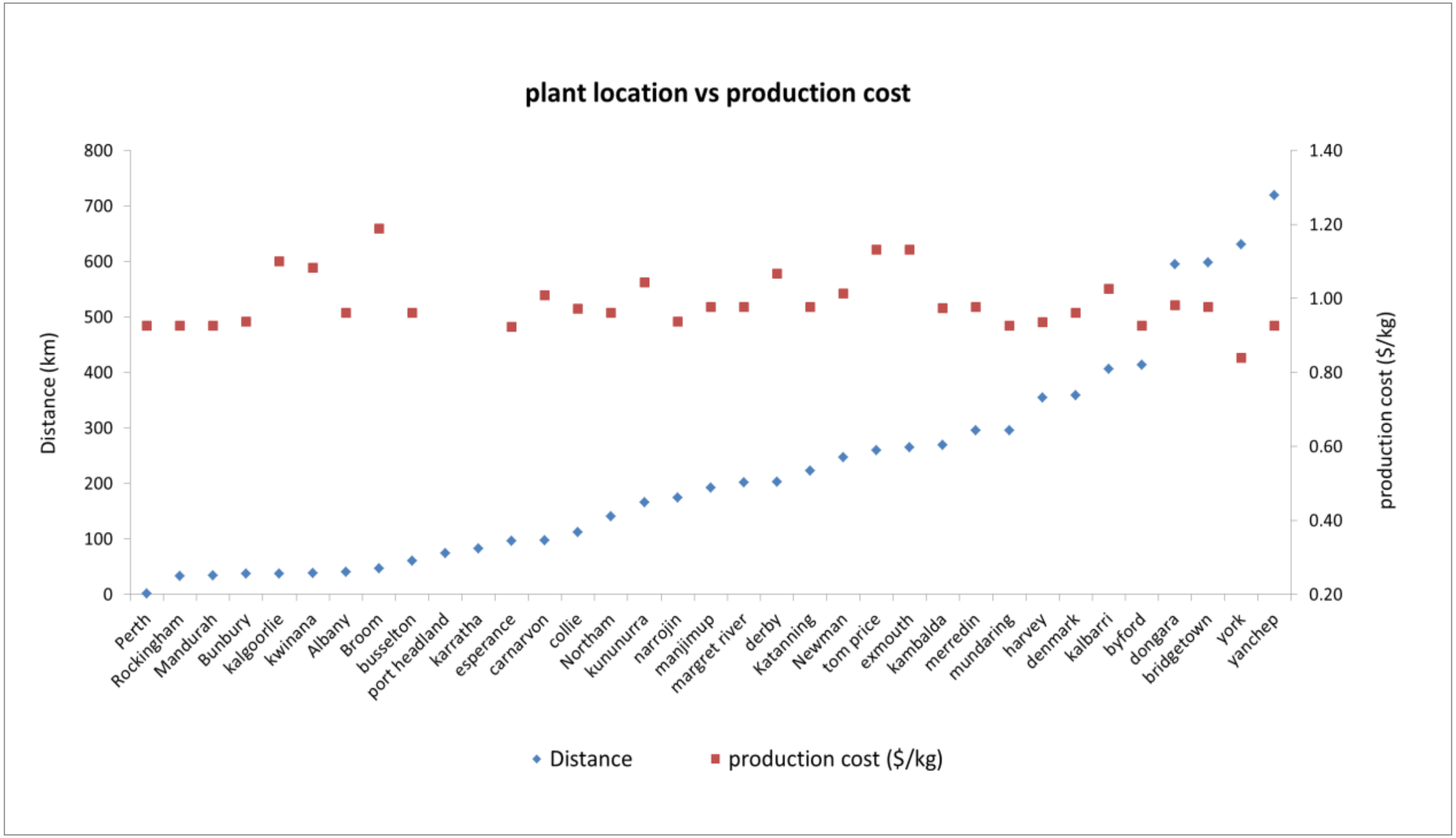

Figure 5-3: The relationship between distance and production costs

Setting the process variables the same and comparing only the land options, the feasibility of the region location was simulated. The results have shown that the abandoned land is not an option due to too high production cost ($27/L biodiesel) caused by the huge infrastructure capital investment. The production cost in Perth CBD and town centre was $0.26/L and $0.20/L respectively assuming the town is 100 km away from CBD area with the relatively low land price. The assessment showed that when the infrastructure cost was twice the capital investment cost, the production cost went soaring. The literature also agreed in that infrastructure expenses only suit high production companies (Alexander & McDonough, 2002). Alexander et al. examined the different sizes of production of eight petroleum exploration wells. They concluded that large quantity of outputs dramatically increased the profit, and the minimum production of the oil plant was 1ML/day to achieve overhead break-even point (Alexander & McDonough, 2002). In this study, the current annual output of biodiesel is 45 ML, which translates to 0.13 ML per day. This is ten times lower than the break-even point of the oil industry. Therefore the biodiesel output is found to be much too small to justify building its own infrastructure and entering the petroleum markets.

5.4.2.2 Individual Localities optimisation

With the regional simulation, it can be argued that the outskirt of town centre would be better suited than the abandoned land or metropolitan area for the bio-refinery plant location. The distance between Perth to the bio-refinery plant is associated with the equipment freight cost, labour related cost, human resource cost, feed and product transportation cost (Seider et al., 2009). These variables were derived from the Holger Nickish economics analyser (Nickish, 2003).

The production cost of transesterification process is analysed and presented in Table 5-9: Production costs of biodiesel from the WCO process. The results of Holger Nickish economic simulation for production cost at each location have shown the relationship between the production costs and the distance. For simplicity of assessment, the fixed distance is used as a function of feedstock collection that is allocated in plant operation costs. Setting all the locations in distance consecutive model, Figure 5-3 has shown that the distance between Perth CBD to the plant should be less than 700 km. This is because the direct freight costs and indirect freight costs increase by more than half the total investment cost, which would negatively affect the business.

After rigorous measurements and accounting for all the variables related to the distance-cost effectiveness, the best location for a new bio-refinery plant is York. Since the land cost in York town is low, hence, its capital investment cost will also be low. In addition, because of the distance from Perth is relatively short (i.e. 98km), so the operating costs will be also low. Moreover, the availability of infrastructure and low labour cost in this town will make it an ideal bio-refinery site. Also, it is a town where the bio-refinery can share the facilities and infrastructure with the local government. This will reduce the capital expenditure drastically. The costs for labour-related operations, maintenance, operations overhead, property taxes and insurance, and depreciation were considered to be fixed costs. The costs did not vary with the production rate but they were an essential element for the bio-refinery plant site selection.

5.4.3 Tortuosity

The collecting truck runs a circle in the metropolitan area every day. To understand the exact freight costs, the tortuosity factor cannot be overlooked. It is a factor between real distances on the road to the linear distance. This concept and calculation have been discussed in depth in the literature (Yu et al., 2009). According to Yu et al., the transport costs sometimes occupy 40% the total production cost. In this study, the values of the tortuosity factor (*f*) were determined from the current road network, and the real distance data is adapted from the MainRoads (mainroads, 2013). The best route for WCO collection and the best bio-refinery location are simulated in Sections 5.4.1 and 5.4.2; however, the simulation results were straight distances.

Now the tortuosity factor is needed to be found in order to get the real distances for this biodiesel process. Tortuosity is calculated by measuring the real distance from the maps divided by the straight distance from the simulations. The smallest tortuosity is 1 if the restaurant is in the city. The maximum distance from Perth to the bio-refinery plant is 700 km in the plant location assessment as described in the last section. Plotting the tortuosity into the graph vs the distance. Figure 5-4 shows that the value of tortuosity factor (*f*) for each town varies due to the form of the road network, and is mainly within the range of 1.11 to 1.44. Within the 700km radial distance, the tortuosity remains at 1.1-1.2 due to many choices of the complex road network, plus the shortest distance for WCO collection is 345 km (see Section 5.4.1). Therefore, the real WCO collection distance is 397 km. As the town distance increases especially up to 1000 km, the tortuosity factor increases from 1.3 to 1.4, this reflects the main roads in Australia following along the coast line. The best plant location is York Town, where it is 98 km from Perth. Thus, the total distance for a heavy-duty truck that collects WCO from all the restaurants and then transports it to the bio-refinery gate is 593 km. This distance will be used in the biodiesel process analysis and life cycle impact assessment later in the last section of this chapter.

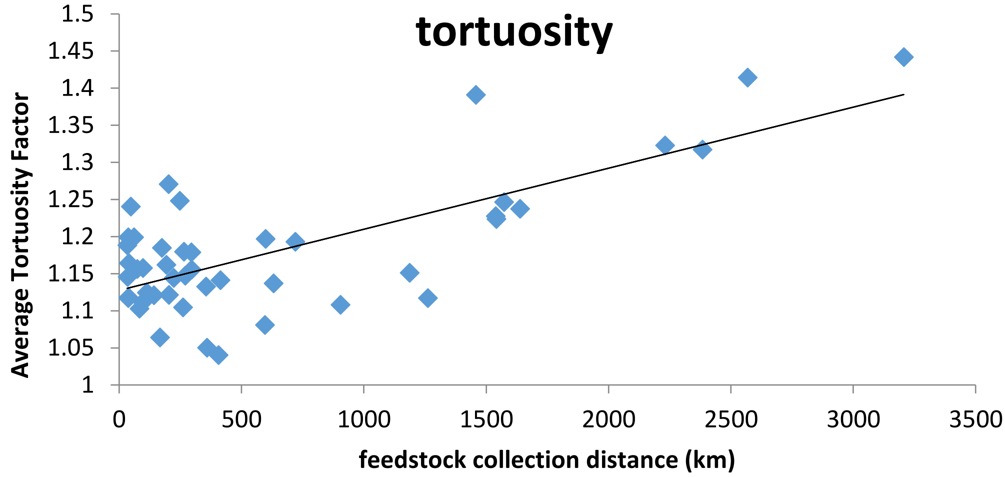

Figure 5-4: Tortuosity of the roads in WA

5.5 Parameters from biodiesel-BMG blend process

In this study, the biodiesel-BMG blend process comprises of two parts: (i) the conventional alkali-catalysed transesterification process with free fat acid pre-treatment process, and (ii) utilising crude glycerol by blend it with bio-oil and methanol to form a new value-added fuel.

With those parameters, the process was simulated and the detailed results are presented in Figure 5.6. The descriptions are in the following sections.

Table 5-2: Transesterification process parameters

Process conditions	**Parameters**
Dry biomass	892.9 kg
Plant capacity	45ML annual [a]
Feed	WCO contains 5% free fat acid [b]
Methanol : oil (molar ratio)	6:1[b]
Transesterification conversion rate	95% [b]
Transesterification catalyst	Sodium hydroxide [b]
Reaction temperature	333.15K[b]
Main product	Biodiesel (>98% purity)
intermediate by-product	Crude glycerol (>20% methanol)
By-product	BMG blend (bio-oil/glycerol/methanol 70:20:10wt %)

[a] Our survey data
[b] Data adapted from literature (Morais et al., 2010)

The process parameters are presented in Table 5-2. All the raw data from our survey and simulations, transesterification process parameters were adapted from the article of Morais et al. (Morais et al., 2010). The ratio of glycerol production to biodiesel is 0.10637, and the feed ratio to biodiesel is 1.042 (Morais et al., 2010). Zhang et al. suggested that the ideal compositions of the bio-oil/glycerol/methanol (BMG) blend were bio-oil ≥ 70wt % glycerol ≤ 20 wt % and methanol ≤ 10 wt % (M. Zhang & Wu, 2014). The green biomass is the product of biomass from the PFT process as described earlier in Chapter 4. The average mallee tree yield is 19.0 dt/ha (Richard J. Harper et al., 2014) and only 892.9kg of biomass is needed for blending in this biofuel process. That means only less than 5% of biomass is employed for the further process, and the rest of the biomass is assumed to be stored on the farm. Then the biomass undergoes the fast pyrolysis reaction to produce bio-oil and biochar. Biochar is used as heat of the pyrolysis equipment and fertiliser. The last stage is blending bio-oil, methanol and crude glycerol into a new fuel, namely BMG blend.

5.6 Mass balances of biodiesel-BMG blend process

The entire process is based on fully recycle the waste cooking oil (WCO) which was generated from Perth metropolitan areas. The quantity of biomass is proportional to the amount of glycerol that is produced from the biodiesel process. The remaining fraction of the harvested biomass is assumed to be stored in the farm storage area in this study.

The traditional biodiesel production process is a well-known process. It involves esterification, transesterification, separation and purifying stages. Here, at hourly rate, 170.0 kg of fresh methanol is fed into the split esterification and transesterification process. 32.4 kg of methanol was recycled into transesterification from the biodiesel purifying distillation column. Up to 194.8 kg of crude glycerol was produced per one-ton feed and contained 24.9% methanol. Approximately 965.0 kg of biodiesel was produced for every one-tonne feed.

This blending process was simulated and the data used were from Chapter 4 and previous sections. Here, 194.8 kg of crude glycerol was produced from the traditional biodiesel process with 24.9% methanol. In the new process, 216.6 kg of fresh methanol was employed. 1623.4 kg of green biomass with 45% moisture content was collected from the surrounding farms to produce 511.7 kg of bio-oil after drying and pyrolysis processes. Finally, 24.4 kg of fresh methanol and crude glycerol were sent to the blender, mixed with bio-oil to produce 649.6 kg of the BMG blend. The blend was comprised of bio-oil, glycerol and methanol with 70, 20, and 10 wt% respectively (M. Zhang & Wu, 2014).

A total 203.6 kg of biochar is produced from the pyrolysis process. Out of the total biochar, 48.86 kg of biochar was used for the heating energy of dryer and pyrolyser. The rest of biochar (154.74 kg) is thrown back to the farm land as fertiliser. The overall mass balances of biodiesel from the WCO process is illustrated in Figure 5-5 and Table 5-3.

Table 5-3: Mass balances of biodiesel-BMG blend process

Feeds	
Waste cooking oil:	1000.0kg
Methanol:	194.4kg
Total other chemicals:	119.5kg
Green biomass (45% moisture [a])	1623.4 kg
Products	
Biodiesel:	965.0 kg
BMG blend	649.6 kg
Waste	18.5kg

[a] Moisture content data is from literature (Yu, 2016)

5.7 Energy balances of the biodiesel-BMG blend process

5.7.1 Energy balance of the biodiesel from WCO process

The energy balance evaluation was based on 1 tonne of WCO feed at 38.94 MJ/kg feed. High heating values were used for energy analysis in this study (Perry, Green, & Maloney, 1997). The total equipment energy requirement was 0.391 MJ/kg feed, and the equipment efficiency was assumed as 80%. The total chemical feeds energy input was 9.5 MJ/kg feed. Among the chemical feed energy, methanol occupied 45% of the total; therefore recycling or purifying the excessive methanol is highly recommended. Results of past research have shown the economic significance of methanol recycling, however, the trade-offs are the energy consumption of recycling the methanol from the process. During the process, the energy input included feed, waste treatment and equipment. Energy output included the product and by-product. The energy balance and conversion efficiency were determined from the ratio of energy output to energy input (Wu et al., 2008). The total energy inputs of the traditional biodiesel process was 9.73 MJ/kg feed excluding energy of WCO itself and the energy conversion ratio was 13.72.

5.7.2 Energy balance of the BGM blend process

The bio-oil sub-process was added into the traditional process for utilising un-purified glycerol and crude bio-oil. It involved two stages, namely drying and pyrolysis. The energy is sufficient in driving pyrolysis to produce biochar as by-product. Therefore, the new process equipment energy consumption is the same as traditional process.

Green biomass contained 45% of moisture content and is assumed to be ash free after the drying process. The plant life time is set at 30 years for pyrolysis process and the bio-oil production ratio to green biomass was 0.3152 (Yu, 2016). The energy balance for the new process from simulation is shown Figure 5-5. The total energy input was 57.33 MJ/ kg feed, the total energy output was 55.23 MJ/kg feed. Among the energy output, BGM blend energy content was 12.39 MJ/kg feed, which is three times higher than for crude glycerol. Biochar is intermediate by-product in this process, the first part of biochar is used to provide the heat of pyrolysis equipment, and the rest of biochar is thrown back to the land as a soil amendment. Although biochar altered the soil nutrient environment but it is effects are not equivalent to that of fertiliser.(Biederman & Harpole, 2013) Hence, this study assumes the biochar contains 70% carbon and carbon sequestration is based on the carbon mass in the biochar.

Table 5-4 has shown the comparison of the energy balances of the two processes. The energy outputs are less than energy inputs for those two processes. However, The net energy gain from biodiesel-BMG process increased from -13.28 to -6.24 MJ/kg feed even the total energy input from biodiesel-BMG process is higher than the total energy input from traditional biodiesel esterification process. It is because of high energy output of the BMG and low energy input of the biomass. The energy inputs of biomass and extra fresh methanol are 0.14 and 0.78 MJ/kg feed respectively, but the energy output from BMG blend is 12.39 MJ/kg feed, that is 2.8 times to crude glycerol. This is an interesting finding and encourages the strategy of by-product utilisation in biodiesel business.

Table 5-4: Energy balance of the biodiesel from WCO process and the biodiesel-BGM blend process

	Biodiesel from WCO process (MJ/kg feed)	Biodiesel–BGM blend process (MJ/kg feed)
Energy input	56.31	57.33
Total Chemicals input	9.4 [c]	9.5
Methanol	3.32 [a]	4.10
Waste cooking oil	38.94 [b]	38.94
Waste	4.26 [c]	4.26
Equipment	0.39 [e]	0.39 [e, g]
Green biomass	NA	0.14 [f]
Energy output	43.04	51.09
Biodiesel	38.7 [h]	38.7
Crude glycerol	4.34 [i]	NA
BGM blend	NA	12.39 [j]
Net energy gain (output-input)	-13.28	-6.24

[a] Methanol high heating value (HHV) was adopted from methanol report (Methanol Institute)
[b] Waste cooking oil HHV was adopted from Fassinou et al. (Fassinou, Sako, Fofana, Koua, & Toure, 2010)
[c] Sulphuric acid, phosphoric acid, calcium oxide, sodium hydroxide and waste HHV were calculated by dollar energy conversion method (SunSirs-China Commodity DATA group, 2016; Wu et al., 2008).
[e] Equipment energy consumption was simulated by ASPEN PLUS 8.4
[f] Biomass data and assumptions were adopted from Yun's unpublished data (Yu, 2016), [g] All biomass equipment energy were fully supplied by Bio-char (Yu, 2016)
[h] Biodiesel HHV data adopted from Mehta et al. (Mehta & Anand, 2009)
[i] Crude glycerol HHV data adopted from Gao et al. (X. Gao et al., 2013)
[j] BGM blend data adopted from Zhang et al. (M. Zhang & Wu, 2014).

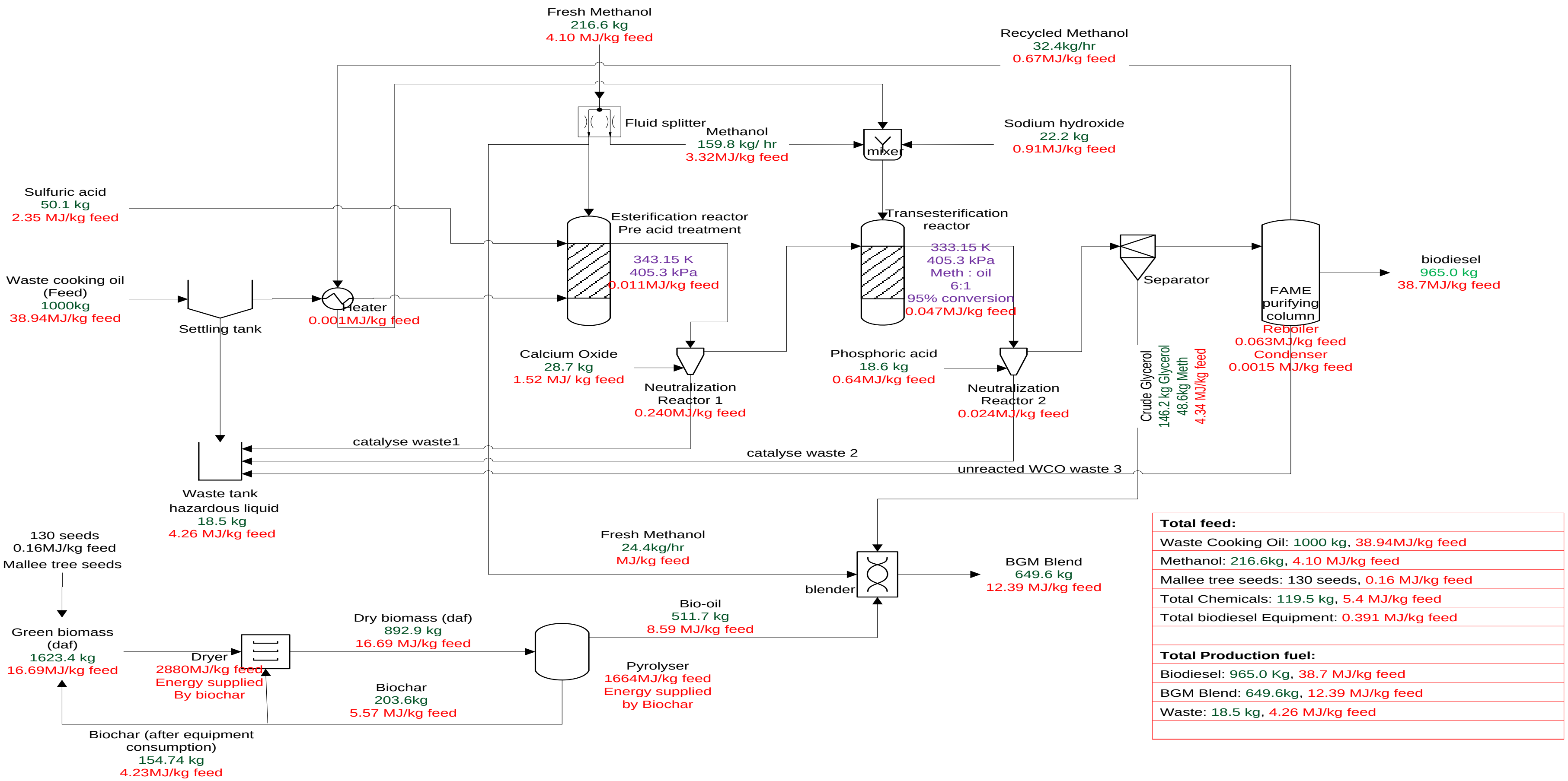

Figure 5-5: Mass and energy balances for biodiesel-BMG blend process

5.8 Functional units and sub-functional units

The functional unit for the biodiesel-BMG blend production process is 1 MJ biodiesel. The by–product is BMG blend. The sub-functional units of energy and carbon footprints are MJ per MJ biodiesel and kg carbon dioxide equivalent (CO_2-e) per MJ biodiesel respectively.

5.9 Life cycle impact assessment

5.9.1 Life cycle energy impact assessment of the biodiesel-BMG blend process

In this section, high heating values were used for energy analysis (Perry et al., 1997). The equipment efficiency was assumed to be 80%. The total amount of energy contained in the biodiesel was set at 38 GJ/t (Mehta & Anand, 2009), and the intermediate by-product glycerol contained 0.45 GJ/t energy (X. Gao et al., 2013).

5.9.1.1 Energy requirements of biodiesel from WCO process

In this section, the collection of waste cooking oil is counted. As mentioned previously in Sections 5.4.2 and 5.4.3, the total distance for a heavy-duty truck that collects WCO from all the restaurants, and then transports it to the bio-refinery gate is 593 km. There are 45 ML of WCO that is collected annually, assuming that every day a heavy duty truck is collecting WCO around the Perth metro area, and then transporting it to the bio-refinery plant in York town. In this case, the collection distance is 5.55 km per 1 ton of WCO. The biodiesel distribution data is from the previous study whereby the biodiesel from canola seeds was distributed to the patrol outlet in the Perth metro area (Rustandi & Wu, 2010). All the results from the simulations are presented in Table 5-5.

Among the chemical feed energy, methanol occupied 84% of the total; therefore recycling or purifying the excessive methanol always got attention. However, the trade-offs of recycling methanol are the energy consumption of recycling the methanol from the process. The overall energy balance of biodiesel-BMG blend process in Figure 5-6 reveals that the equipment energy consumption is 5 % of total energy input, the energy consumption of the heat and electricity of the process is 7% of total energy input, and energy consumption of transport is 3%. There is not energy input from WCO itself because it is considered as a waste, thus giving the energy conversion ratio of 8.15. It follows that recycling methanol will worsen the energy conversion performance. Therefore, another option of improving the biodiesel process performance is utilising the crude glycerol directly instead of recycling methanol from crude glycerol. The BMG blend option was proposed by Mingming Zhang (M. Zhang, 2015b) and this is assessed in the following sections.

Table 5-5: Primary energy requirements of biodiesel from the WCO process

Inputs	**kJ /MJ biodiesel**
WCO collection	0.53
Chemicals	17.15
Methanol	92.74
Equipment heat & Electricity	9.12
Biodiesel distribution	3.08
Total	**122.62**

5.9.1.2 Energy requirements of biomass from the PFT system

As mentioned previously in Chapter 4, according to the mass balances, with 38700 MJ main product – biodiesel, only one by-product is related to biomass from the PFT system, which is 13018 MJ BMG blend. This particular BMG blending process only require less than 5% biomass when the biomass production is 19.0 dt/ha. Taking into account of the energy required per hectare, the corresponding total primary energy requirement is 13.36 kJ/MJ biodiesel. These results are presented in Table 5-6.

Table 5-6: Primary energy requirements of biomass production from the PFT system

Energy Input	MJ/ha	kJ/MJ biodiesel
Site preparation & management	1319	1.60
Planting	1600	1.94
Harvesting (tree pulling & Mulching)	4560	5.54
Woody biomass transportation	3771	4.58
Total	**11250**	**13.36**

5.9.1.3 Overall energy footprint of the biodiesel-BMG blend process

There are two products that are produced from this biodiesel-BMG blend process as shown previously in Section 5.2. In this study, the biodiesel is the main product and the by-product is BMG blend from the biodiesel-BMG blend process.

With 1-ton of WCO feed, the overall detailed life cycle energy impact is shown in Figure 5-6. The most energy intensive product is biodiesel. The biodiesel from WCO process consumes 128.7 kJ/MJ biodiesel, the bio-oil from biomass consumes 31.6 kJ/MJ biodiesel, and 13.05 kJ/MJ biodiesel was consumed by fresh methanol in blending process. Overall, 80% of the total energy requirement for the biodiesel-BMG blend process is consumed by the transesterification process, mainly is consumed by chemicals of the transesterification process which 90% of total energy requirement; 3% of the total energy requirement is consumed by transportation sector, and 7% of total energy requirement is consumed by the process heat and electricity.

In the biomass production stage, the energy is mainly consumed by the transportation section, farm implements, and fuel consumption. Compare to the overall biodiesel-BMG process, the energy requirement of the biomass production section is less than the biodiesel process section, which is 13.36 kJ/MJ biodiesel as shown in Figure 5-6.

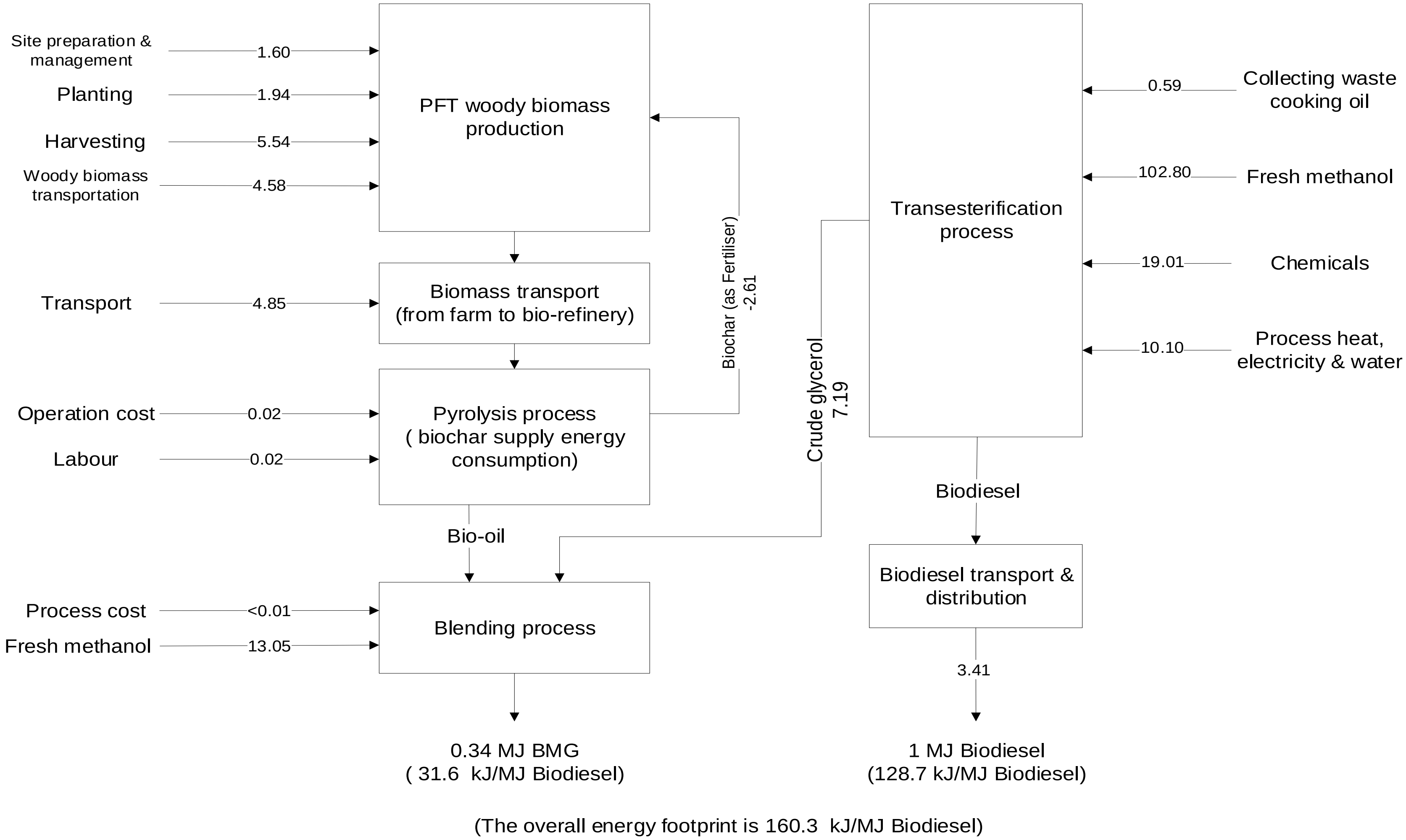

Figure 5-6: Energy footprint of the biodiesel-BMG blend process system (the unit for all the numbers is kJ/MJ biodiesel)

In this study, biochar from the pyrolysis process is thrown back to the land as fertiliser, it is large amount energy back to the land, some of the energy is used by plants; some of the energy remains in the soil. This is a complicated issue and further study of biochar fertilisation is recommended.

5.9.2 Life cycle carbon impact of the biodiesel-BMG blend process

In this study, the average mallee tree yield is 19.0 dt/ha (Richard J. Harper et al., 2014) and only 892.9kg of biomass is needed for blending in this biofuel process. That means only 6% of biomass is employed for further process and the rest of the biomass is assumed to be stored on the farm.

5.9.2.1 GHG emissions of biodiesel from WCO and pyrolysis processes

In this study, the GHG emission or carbon embedded in waste cooking oil itself is excluded. GHG emissions from this process include transport, chemicals and utilities. The results are from the GREET model simulation are presented in Table 5-7.

Table 5-7: GHG emissions of biodiesel from WCO and the pyrolysis process

Carbon emission	**g CO_2-e/MJ biodiesel**
WCO collection	0.04
Chemicals	30.14
Equipment heat & electricity	37.14
Biodiesel distribution	1.20
Pyrolysis reaction	0.00
Product	
Biodiesel	61.67
Crude Glycerol	6.85

The single largest contributor of GHG emissions is equipment heat & electricity (37.14 gCO_2-e/MJ biodiesel) that are employed during the process; this is 48% of the total GHG emissions of the biodiesel and pyrolysis process. The second largest contributor of GHG emissions is chemicals (30.14 gCO_2-e/MJ biodiesel) from the esterification process; this is 36% of the total GHG emissions of the biodiesel and the pyrolysis process. Different to the energy footprint of the biodiesel-BMG blend process, transport sector does not contribute significant amount GHG emissions.

5.9.2.2 GHG emissions of biomass production from the PFT system

The direction of changes of soil organic carbon is influenced by land-use and land-use-change (i.e., re-forest on arable lands or convert native forests to farmlands). This is analysed by using the FullCAM model and the results are presented in Table 5-8.

The GHG emissions from farming activities are 0.38 g CO_2-e/MJ biodiesel which includes the emission in LULUC sector. The GHG emission from pyrolysis reaction is zero in this study because the energy of the pyrolysis reaction comes from biochar and it is self-sufficient. The GHG emission in LULUC is -0.01 g CO_2-e/MJ biodiesel. The negative carbon emission indicates that carbon is sequestrated from the atmosphere into plantations and soils. Here, the above- and below- ground biomass is assumed to be eventually combusted for energy recovery, the carbon sequestrated into which will be released to atmosphere again, therefore, the carbon sequestrated into biomass is not considered in determining the carbon footprint for biomass production. From this perspective, the SOC gain is more important in determining the overall GHG emissions from the biodiesel-BMG blending process.

Although the carbon sequestration from LULUC is less than -0.01 g CO_2-e/MJ biodiesel, this finding encourages stakeholders and researchers to take land-use change into account because of scald lands are corrected.

5.9.2.3 Overall GHG emissions of the biodiesel-BMG blend process

Biodiesel- BMG blend process is a blending process for utilising crude glycerol by blending bio-oil, glycerol and methanol into BMG blend. The overall GHG emissions are shown in Figure 5-7. The GHG emissions of biodiesel-BMG blend process are

55.7 g CO_2-e /MJ biodiesel including the carbon sequestration to the reforest plantation.

Table 5-8: GHG emissions of biomass production from the PFT system and pyrolysis reaction

GHG emissions	**g CO_2-e/MJ biodiesel**
PFT farming	
Site preparation & management	0.24
Direct seeding and planting	0.17
Harvesting	0.07
Woody biomass transportation	0.39
Land-use and land-use-change	-0.01
Pyrolysis and blending processes	
Fresh methanol	1.38
Crude glycerol	3.41
Biochar recycle fertilising	-12.63

The largest single GHG emission is from transesterification process (37.10 g CO_2-e /MJ biodiesel). It occupies nearly half of the total GHG emissions of the entire process. The second largest GHG emission is from chemicals during transesterification process (30.14 g CO_2-e /MJ biodiesel). The GHG emission from WCO collection is 0.04 g CO_2-e /MJ biodiesel, mainly from fuel and oil. This amount of GHG emission is less than 1% of total GHG emissions in the biodiesel-BMG blend process. However if the entire fossil diesel is replaced by biodiesel in this study, that will help CO_2-e savings in the process.

The carbon footprint in biomass sector is more interesting than in biodiesel from the WCO process. This study assumed that the biochar from the bio-oil pyrolysis process is thrown back to the land as fertilizer. This makes huge difference in carbon sequestration. After the first part of the biochar is consumed for the pyrolysis heating process, the rest of biochar (i.e. 155 kg) is applied into soil as fertiliser. This sequestrates 12.63 g CO_2-e/MJ biodiesel of the process. The total GHG emissions of the BMG blend is -13.3g CO_2-e /MJ biodiesel including carbon sequestration from reforest plantation, and the carbon sequestration is only -0.01 g CO_2-e /MJ biodiesel from LULUC. The negative carbon emission from LULUC indicates that carbon is sequestrated from the atmosphere into soil.

Results of simulations have shown that the amount of sequestrated carbon from atmosphere by reforest plantations is trivial, but the negative carbon emission from biochar fertilisation is significant. The total carbon emission of biodiesel-BMG blend process is 55.7 g CO_2-e /MJ biodiesel. The total carbon emissions of biodiesel from transesterification process is 69.0 g CO_2-e /MJ biodiesel. That means the carbon emission from BMG blend is less when compared to the GHG emissions from the transesterification process.

In this study, the BMG blend is assumed to be used as a fuel and to be burned, therefore, the carbon sequestration into the forest is not counted. If the BMG blend is used with a purpose other than burning, perhaps the carbon footprint of the BMG-blend process will be more interesting and has to be recalculated. This is the ultimate goal of the carbon footprint assessment – to sequestrate carbon dioxide from the atmosphere but not release it to the atmosphere again. It is the future work to be pursued by all researchers in the world.

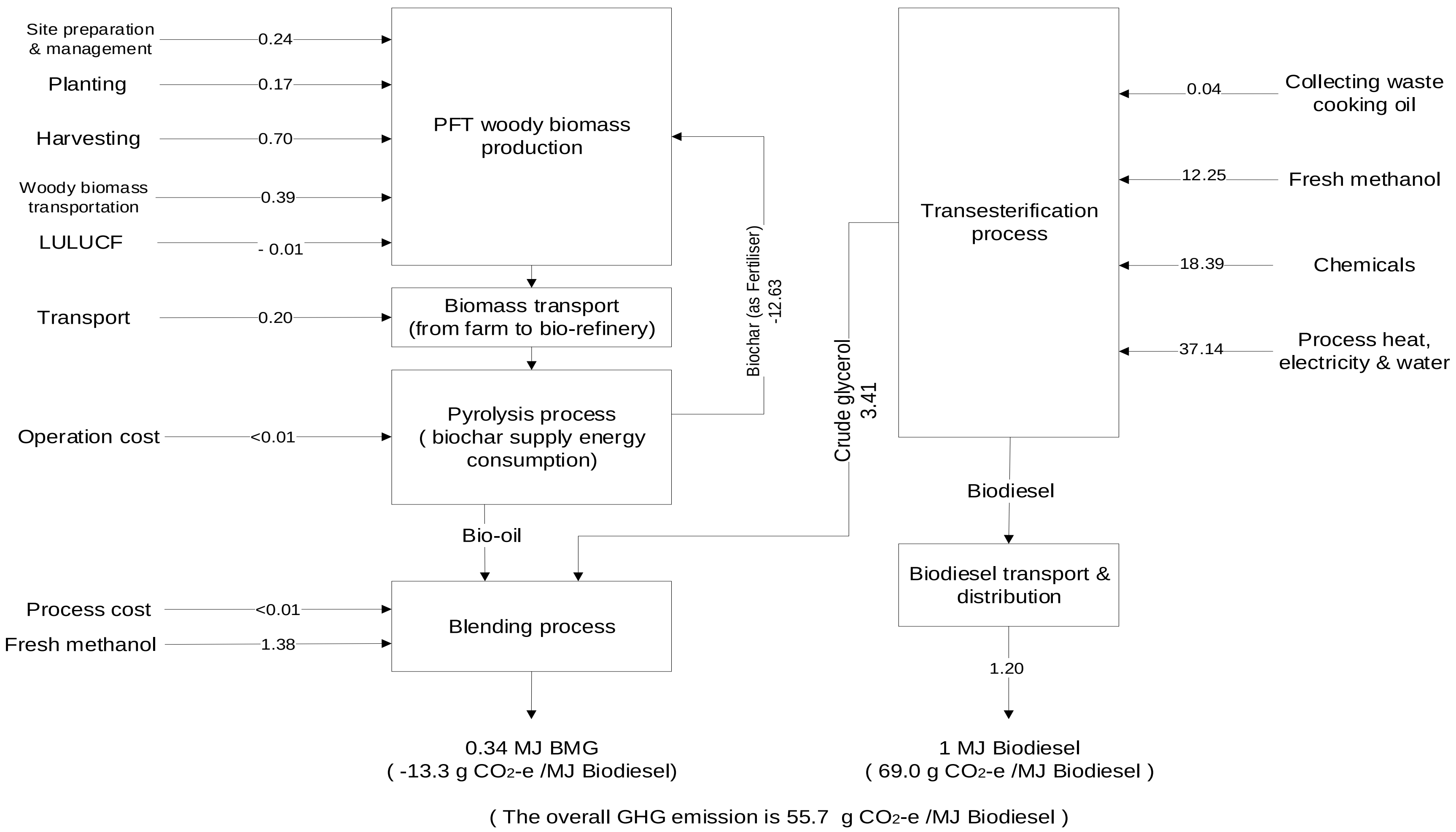

Figure 5-7: Carbon footprints of the biodiesel-BMG blend process system (the unit for all the numbers is g CO_2-e/MJ biodiesel)

5.10 Production cost analysis of biodiesel-BMG blend process

5.10.1 Production cost analysis of biodiesel from WCO process

The production costs of traditional biodiesel process at York town have been estimated and the details are shown in Table 5-9. The total equipment costs included the equipment and installation by using the bare-module; 94 km from York town to Perth was counted while calculating the equipment installation. Transportation cost also affects personnel costs, engineering working overheads, sales cost and maintenance or operation costs (Seider et al., 2009).

Table 5-9: Production costs of biodiesel from the WCO process.

Production costs at York town		**Costs**
Total capital investment		
Total equipment cost ($)		4021826
Permanent investment capital ($)		1693600
Working capital ($)		8187400
	sub-total A	13902826
Annual variable costs		
Raw materials ($)		3276529
Utilities ($)		1994500
Transport cost($)		1527400
Other admin expenses ($)		3827300
Management incentives($)		708800
	sub-total B	11334529
Annual fixed costs		
Operations ($)		595000
Maintenance ($)		602267
Insurance, taxes($)		116380
	sub-total C	1313647
Production cost ($/kg)		0.83
Crude Glycerol credit ($/kg)		-0.11

The capital investment costs $13 million, the cost of raw materials is $3 million and $1.3 million is accounted for annual fixed costs. The production cost in this traditional process was $0.83/kg biodiesel, as shown in Table 5-9. The market price of biodiesel (B99- B100) is $1.09/kg and the gross margin is $0.34/kg biodiesel that includes $0.11/kg crude glycerol as credit (Energy Efficiency & Renewable Energy, 2016).

5.10.2 Biodiesel from WCO process costs allocation

The traditional biodiesel process costs allocation clearly revealed the major factors of plant driving force. Figure 5-8 has shown the capital cost only occupied 3% of the total, less than 10% was for the fixed variables, and with more than 86% as were variable costs. Among the variable costs, raw materials, utilities and transport costs occupied 25%, 15% and 12% respectively. This indicates that these variables significantly affect the plant economic performance.

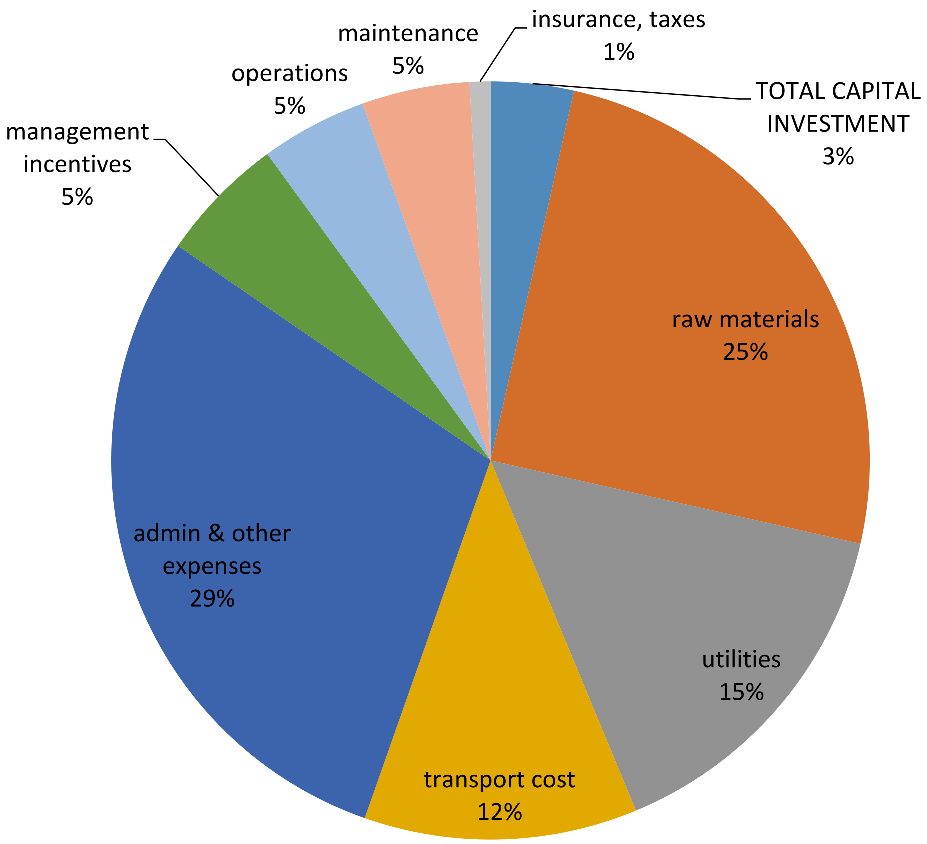

Figure 5-8: Breakdowns of biodiesel from the WCO process costs allocation.

5.10.3 Production cost analysis of biodiesel-BGM blend process

Figure 4-2 has illustrated the full quantity of energy inputs of biomass forestry production for the duration of 4 years. Energy includes capital, fuel, labour, land and water. The process costs are simulated by the Revegetation Project Modelling and Costs (RPMC) simulator. The process costs contain project planning and management, transport, seeds, seeding, tree guard costs and site supervising (Schirmer & Field, 2010; Wu et al., 2008).

As shown in Table 5-9 the capital cost of the new process was $14m, but the capital cost remained almost the same as the traditional process because there were only two additional items of equipment added into the traditional items of process, namely dryer and pyrolyzer. The raw material included the green biomass, $5.6m per year. The costs of other variables such as utilities, transport and admin expenses were $1.9m, $1.5m and $3.8m respectively. These variables also affected the business performance through market prices. After all the parameters were set out and identified, the analysis of production costs was carried out for the economic evaluation of the new process.

The production cost was $0.98/kg for the biodiesel in the new process, but BGM blend and bio-char have gained credits of $0.38/kg and $4.47/kg respectively (Jirka & Tomlinson, 2014). Hence, the overall production cost for the new process was $0.40/kg, which is much less than the fossil fuel prices. Thus the gross margin was $0.69/kg biodiesel which is very attractive. Therefore, the prices of by-products are vital for the business decision making which makes this process quite unique and economically sustainable.

5.10.3.1 BMG blend value evaluation

The BMG blend is the only by-product of the new process. It can be used in a direct combustion as a burner fuel in direct fired burners because of it is a homogeneous mixture and high alcohol content, for example, furnaces in fire stations or explosion equipment.

It is a non-trivial factor for determine the economic performance of a new fuel process. The BGM blend does not have any market value as it is a new type of fuel. Nevertheless, the market price of fuels is proportion to high heating value (HHV).

Hence the market value can be predicted by looking at the relationship between HHV and fuel's market value. Table 5-10 has shown the relations between HHV and the market price, and the predicted BGM blend price was $0.378 / kg.

Table 5-10: BMG Blend Fuel Price Predictions

	HHV(MJ/kg)	Price ($/kg)
Diesel	45.76[a]	1.181[c]
Biodiesel	40.16 [a]	0.664 [c]
Gasonline	46.52 [a]	1.504 [c]
Methanol	22.88 [a]	0.406 [d]
BGM blend (predicted)	19.08[b]	0.378*

[a] Data are adapted from U.S Department of Energy website (U.S.Department of Energy, 2016)
[b] Data were adapted from Zhang's publication (M. Zhang, 2015a)
[c] The retail prices are adapted from government annual study(*Pump Prices (Retail)*, 2016)
[d] The retail price is adapted from the website (Altona Energy, 2013) *Calculated data

5.10.3.2 Production cost of biodiesel-BGM blend process

As shown in Table 5-11, the capital cost of the biodiesel-BGM blend process was $14m dollars, the capital cost remained almost the same as biodiesel from WCO process because there were only two additional equipment's added into the traditional process- dryer and pyrolyzer. The cost of raw materials included the green biomass was $5.6m per year. Other variables such as utilities transport and admin expenses were $1.9m, $1.5m and $3.8m respectively. These variable costs were also influenced by the market prices and therefore affecting the business performance. The annual variable costs need to be monitored annually to predict the business future.

The price of BMG blend in this study was calculated as $0.378/kg (see section5.10.3.1). However, the price can be higher if it is more accepted by public. According to our predicted price, the production cost of biodiesel is $0.98, the BMG blend could gain credit $0.38. The biodiesel-BMG blend process can almost halved biodiesel process cost. It is a remarkable achievement. The BMG blend is a truly value-added by-product. Although the annual variable costs and other costs are affected by the market then affect overall business performance, however, this new process can push biodiesel industry onto a new stage.

Table 5-11: Production costs of biodiesel-BGM blend process

Production costs at York town		**biodiesel-BGM blend process**
Total capital investment		
Total equipment cost ($)		4482300
Permanent investment capital ($)		1693600
Working capital ($)		8186600
	Sub-total A	14362500
Annual variable costs		
Raw materials ($)		5575400
Utilities ($)		1993900
Transport cost($)		1527400
Admin other expenses ($)		3827300
Management incentives($)		708800
	Sub-total B	13632800
Annual fixed costs		
Operations ($)		595199
Maintenance ($)		602267
Insurance, taxes($)		116380
	Sub-total C	1313846
Production cost ($/kg)		0.98
Predicted BMG blend credit ($/kg)*		-0.38

5.10.3.3 Biodiesel-BGM blend process costs allocation

Figure 5-9 illustrates the cost allocation of the bio-refinery plant, where raw materials occupy 36% of the manufacturing cost. This figure and Table 5-9 emphasised that 86% of the total cost is for variable cost, and 11% of the total cost is for production-related fixed costs. This is because of the high costs of raw materials, particularly biomass, where the green biomass accounted for 41% of the total raw material costs. This interesting finding suggests that the profitability of the plant is strongly linked to the biomass price. However, due to Australia's unique geometrical character, it is not easy to reduce the price of biomass. Yun et al. had assessed all direct and indirect costs to produce the biomass pellets as bio-oil raw materials, and have determined the green biomass manufactory costs to be $34/t in WA (Yu, 2016). Based on their data, we estimated the green biomass cost to be $1.2m annually.

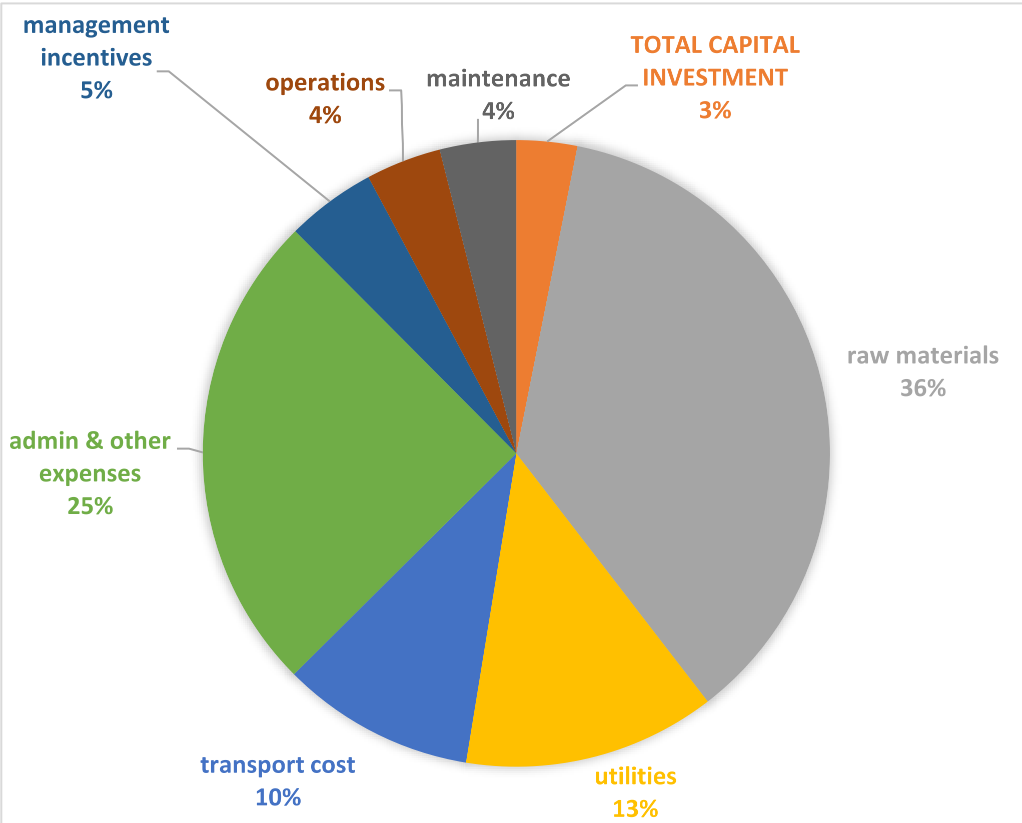

Figure 5-9: Breakdowns of production costs of the biodiesel & blend production

5.11 Conclusions

- Chapter 5 revealed the improvement of biodiesel from the WCO process by blending crude glycerol with bio-oil to form a new value-added fuel. Zhang et al. proposed and investigated a new type of fuel blend – bio-oil/methanol/glycerol (BMG) (M. Zhang, 2015b; M. Zhang & Wu, 2014). This chapter has investigated the energy carbon footprints of this blending process and its economics.
- Section 5.9.1 has analysed the energy footprint of the biodiesel transesterification process and the biodiesel-BMG blend process. The energy ratio was 1.2 for the biodiesel transesterification process, and the energy ratio was 1.6 for the biodiesel-BMG blend process. Thus by blending crude glycerol into bio-oil to form a new fuel, the overall energy footprint is improved by 30%.
- Section 5.9.2 has revealed the carbon footprint of the biodiesel transesterification process and the biodiesel-BMG blend process. GHG emissions from the biodiesel transesterification process were 69.02 g CO_2-e/MJ biodiesel. The GHG emissions embedded in crude glycerol was 6.90 g CO_2-e/MJ biodiesel. The GHG emissions from the biodiesel-BMG blend process were 55.7 g CO_2-e/MJ biodiesel whereby the GHG emission from the pyrolysis reaction was 0 g CO_2-e/MJ biodiesel. The carbon sequestrated into soil was -0.01 g CO_2-e /MJ biodiesel. In conclusion, the overall carbon footprint of the biodiesel-BMG blend process was similar to the biodiesel transesterification process.
- The transportation assessment in Section 5.4 has shown that the best location of the bio-refinery plant is in York town. Since the land cost in York town is low, its capital investment cost will also be low. In addition, because of the distance from Perth is relatively short (i.e. 98km), so the operating costs will also be low. Even with the most economic bio-refinery location, economic analysis of biodiesel from the WCO process in Section 5.10 shown that this biodiesel from WCO process has very low profit to attract investors. The business break–even point is where the production cost meets the profit from sales.

- Zhang et al. proposed and investigated a new type of fuel blend – bio-oil/methanol/glycerol (BMG) (M. Zhang, 2015b; M. Zhang & Wu, 2014). Following the study of the biodiesel-BMG blend process, this study recommended that this new process integrates both biodiesel process and bio-oil process by blending crude glycerol into bio-oil without the glycerol phase separation and neutralisation stage, to form a value-added fuel. Section 5.10 has found that the production costs would be halved when the BMG blend process is combined with the biodiesel process.
- Overall, the biodiesel-BMG blend process is more attractive economically and is advanced in utilising the abundant by-product, i.e., crude glycerol.

Chapter 6 Biodiesel-BGB slurry Process

6.1 Introduction

Life cycle analysis of the bio-oil/methanol/glycerol blend was conducted in the last chapter and the results were encouraging, and biochar was stored as a by-product of the pyrolysis process. However, biochar as a high-energy-density solid by-product may lead to potential environmental hazard during transportation and storage phase due to its fine particle size and combustible characteristic (e.g. dusty (X. Gao & Wu, 2014) or spontaneous combustion (Wu, Yu, & Yip, 2010)). Hence suspending biochar particles into crude bio-oil or other low-grade liquid biofuels as bioslurry fuel has been considered as a double win strategy since bioslurry becomes another fuel option while the environmental hazard of biochar is limited.

The main combinations of bioslurry fuels are bio-oil/biochar and bio-oil/glycerol/biochar, namely BB slurry and BGB slurry respectively. Those bioslurry fuels have been studied in depth by Wu and co-workers (Abdullah, Mourant, Li, & Wu, 2010; Abdullah & Wu, 2011; W. Gao et al., 2016; Ghezelchi, Garcia-Perez, & Wu, 2015; Wu et al., 2010; Yu & Wu, 2010; M. Zhang, 2015a; M. Zhang, Gao, & Wu, 2013; M. Zhang, Liaw, & Wu, 2013). Studies on the properties and characteristics of bioslurry fuels have shown its non-Newtonian and thixotropic behaviour (W. Gao et al., 2016; M. Zhang, Liaw, et al., 2013). Those findings have encouraged studying further studies on bioslurry fuels, such as economic viability and life cycle assessments. Those studies have found the bioslurry fuel to be economical viable. Gao and co-workers studied the BGB and they found BGB slurry fuel has higher heating value, lower viscosity, water content and total acids number when compared to bio-oil/biochar slurry fuel (W. Gao et al., 2016).

The properties and flow behaviours of bioslurry fuels have been researched in depth. However, only a few studies on the energy and carbon footprints of the BB bioslurry fuel have been conducted (Yu & Wu, 2010). Unfortunately, up to now, no data are available in the published literature on the energy and carbon footprints of BGB slurry fuel. Such data are important to assess the overall sustainability of BGB slurry as a fuel. Therefore, the objective of this chapter was to investigate the life cycle assessment on the BGB slurry. The energy and carbon footprints of the BGB slurry from the previous chapter are analysed based on mallee biomass in WA.

6.2 Boundary of the BGB bioslurry production process

Figure 6-1 has shown the overall description of the BGB bioslurry production that produces biodiesel and the BGB bioslurry from mallee tree seeds and waste cooking oil from the metropolitan area in Perth.

Biomass and biodiesel productions were described previously in Chapters 4 and 5. Woody biomass is from the PFT system by assuming that a fraction of biomass is separated from a mean of 19.0 dt/ha biomass production process. Less than 5% biomass per hectare is used for the bio-oil process and mixed with biochar and the crude glycerol from transesterification process. Biodiesel with purity >98% was achieved from this transesterification simulation, and it is assumed to be used as transportation fuel.

The biomass from the PFT system is harvested and transported to the bio-refinery plant, followed by drying and the fast pyrolysis reaction to produce bio-oil. Both bio-oil and biochar are the products of the fast pyrolysis reaction. The biochar is ground to particle sizes below 75 μm, and then it is mixed with bio-oil and crude glycerol to form a new final product – BGB slurry. This BGB bioslurry comprises of bio-oil, crude glycerol and biochar in 60, 22 and 18 wt% respectively. It is important to note that the solid concentration of the BGB slurry in this study is 18 wt%.

In this study, all the farm activities, land used and land use change, transportation and chemicals used for transesterification process, equipment of the process, labour and process heat etc. are all included in the life cycle assessment, irrespective of whether indirect energy or direct energy is consumed in the process.

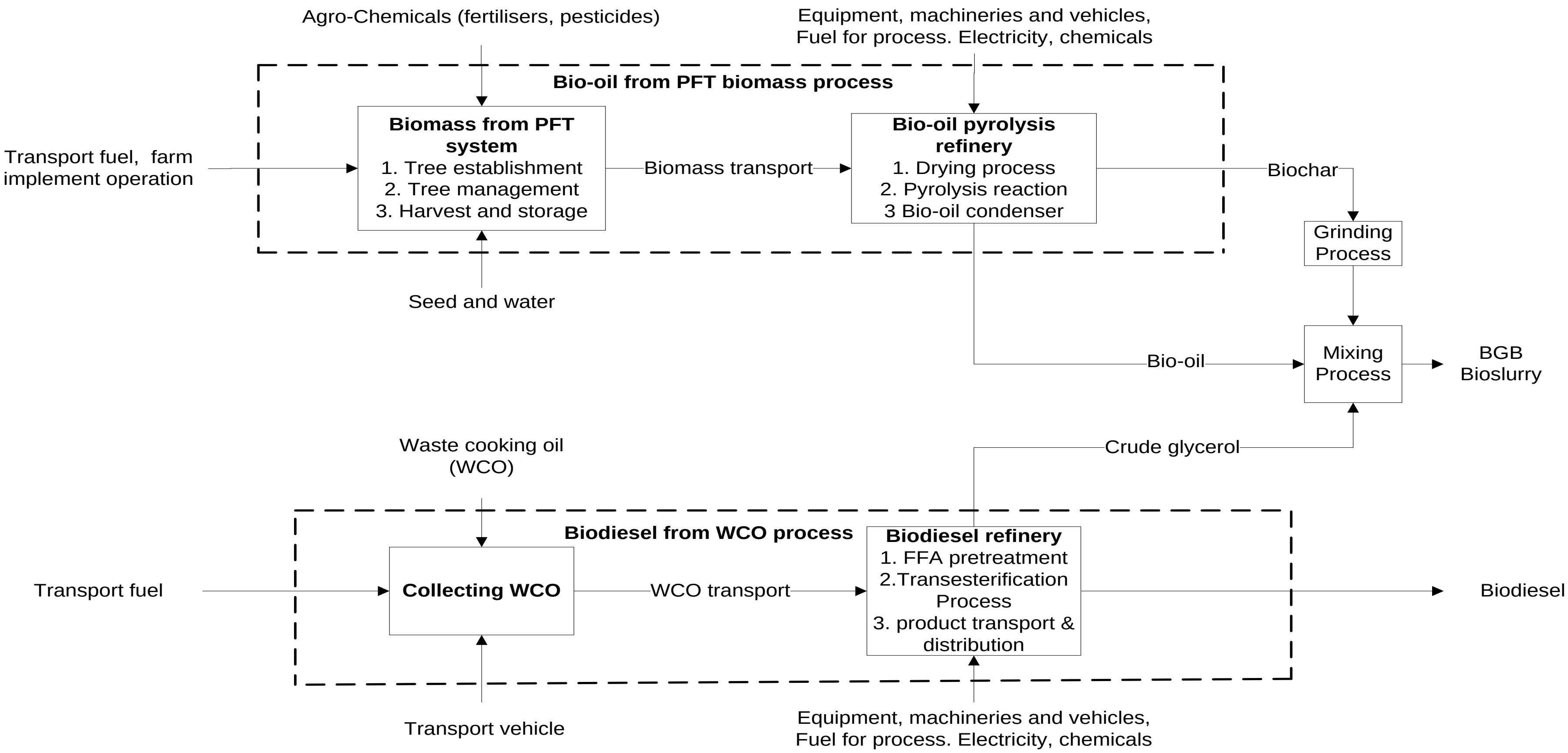

Figure 6-1: Boundary of the BGB bioslurry production process

6.3 Parameters from the BGB slurry process

In this chapter, the BGB slurry process comprises of two parts: (i) the conventional alkali-catalysed transesterification process with free fat acid pre-treatment process, and (ii) utilising the by-products – biochar and crude glycerol by mix them with bio-oil to form a new value-added fuel – BGB slurry.

Table 6-1: Biodiesel- BGB slurry process parameters.

Process conditions	**Parameters**
Dry biomass	892.9 kg
Plant capacity	45ML annual [a]
Feed	1 ton WCO contains 5% free fat acid [b]
Methanol : oil (molar ratio)	6:1[b]
Transesterification conversion rate	95% [b]
Transesterification catalyst	Sodium hydroxide [b]
Reaction temperature	333.15K[b]
Main product	Biodiesel (>98% purity)
Intermediate by-product	Bio-oil
Intermediate by-product	Crude glycerol (>20% methanol)
Intermediate by-product	Biochar (<75 μm) [c]
By-product	BGB slurry (biochar 18 wt%)

[a] Our survey data, [b] Data were adapted from literature (Morais et al., 2010), [c] Data were adapted from literature (W. Gao et al., 2016)

The parameters of the transesterification and BMG blending processes are adapted from Chapters 4 and 5. These parameters are presented in Table 6-1. The feeds are 1 ton WCO and 892 kg dry biomass. The intermediate by-products are crude glycerol (> 20% methanol), 511.7 kg bio-oil, and 154.7 kg of biochar. Those by-products are mixed into the mixer to form the BGB slurry. With those parameters, the process was simulated and the detailed results are presented in Figure 6-1. The descriptions are in the following sections.

6.4 Mass balances of the biodiesel-BGB slurry process

This biodiesel-BGB slurry mixing process was simulated and the data used were from Chapters 4 and 5. It is similar to the biodiesel-BMG blend process but with one value-added by-product – BGB slurry. The entire process is based on fully-recycled the waste cooking oil (WCO) that was generated from Perth metropolitan areas. The quantity of biomass is proportional to the amount of glycerol that is produced form the biodiesel process. In this study, the remaining fraction of the harvested biomass is assumed to be stored in the farm storage area.

Table 6-2: Mass balances of the biodiesel-BGB slurry process.

Feeds	
Waste cooking oil:	1000.0kg
Methanol:	192.2kg
Total other chemicals:	119.5kg
Green biomass (45% moisture [a])	1623.4 kg
Products	
Biodiesel	965.0 kg
BGB slurry	804.3 kg
Waste	18.5kg

[a] Moisture content data is from literature (Yu, 2016)

The biodiesel transesterification production process is the first part of the biodiesel-BGB slurry process, and it was described in Chapter 5. The second part of the biodiesel-BGB slurry process was bio-oil from the fast pyrolysis process. Here, 1623.4 kg of green biomass with 45% moisture content was collected from the surrounding farms to produce 511.7 kg of bio-oil and 154.74 kg biochar after the drying and pyrolysis processes. After the biochar was ground to sizes less than 75 µm, 194.8 kg of crude glycerol and 154.74 kg of biochar were mixed with 511.7 kg of bio-oil to produce 804.3 kg of the slurry, namely BGB slurry. The compositions of this BGB slurry were bio-oil, crude glycerol and biochar in 60, 22 and 18 wt% respectively; so the BGB slurry contained 19.2 wt% solid. The data of mass balance of biodiesel-BGB slurry process is presented in Table 6-2 and Figure 6-2.

6.5 Energy balances of the biodiesel-BGB slurry process

The energy balances of the biodiesel-BGB slurry process comprise of two parts; the first part is the energy balance of biodiesel from WCO process and the details were described in Section 855.7.1. The bio-oil sub-process was added into the traditional process for utilising crude glycerol and bio-oil. This process was also described in Section 4.4.2.1.

The second part of the energy balance was from BGB slurry process. It included three stages: namely drying, pyrolysis and mixing. The energy is sufficient in driving pyrolysis to produce an intermediate by-product – biochar. Therefore, the energy consumption of the new process equipment is the same as the traditional process. Green biomass contained 45% of moisture content and is assumed to be ash-free after the drying process. The plant life-time is set at 30 years for the pyrolysis process and the ratio of bio-oil production to green biomass was 0.3152 (Yu, 2016). The energy balance for the new process from simulation was shown in Figure 6-2. The total energy input was 48.99 MJ/ kg feed, and the total energy output was 45.32 MJ/kg feed. Among the energy output, the BGB slurry energy content is 16.62 MJ/kg feed. This is four times higher than for crude glycerol.

The net energy gain is -3.67 MJ/kg feed. It means the biodiesel-BGB slurry process is not energy efficient. The single largest energy consumption is from chemical input in transesterification process, which is 5.4 MJ/kg feed. The process equipment does not consume too much energy that because pyrolysis and drying equipment are self-energy supplied by biochar. These results have shown the significant improvement compare to methanal recycling from crude glycerol process.

The bioslurry is a double-win strategy for energy saving aspect. Instead spending energy to recycle excess alcohol from crude glycerol, it combines bio-oil and biochar to provide energy for other combustion applications. It has saved the energy from methanol recycling; also provided the energy as a new type of fuel for other applications. However, the waste from the process contains 4.26 MJ/kg feed energy. If the energy from the waste can be saved, then the net energy gain will be positive.

Table 6-3: Energy balance of the biodiesel-BGB slurry process.

Energy consumption	Biodiesel-BGB slurry process (MJ/kg feed)
Energy input	48.99
Methanol	3.64 [a]
Waste cooking oil (feed)	38.94 [b]
Total Chemicals input	5.4 [c]
Waste	4.26 [c]
Equipment	0.391 [d, f]
Mallee tree seeds	0.16 [e]
Energy output	45.32
Biodiesel	38.7 [g]
BGB slurry	16.62 [h]
Net energy gain (output – input)	-3.67

[a] Methanol high heating value (HHV) was adopted from methanol report (Methanol Institute),
[b] Waste cooking oil HHV was adopted from Fassinou et al. (Fassinou et al., 2010),
[c] Sulphuric acid, phosphoric acid, calcium oxide, sodium hydroxide and waste HHV were calculated by dollar energy conversion method (SunSirs-China Commodity DATA group, 2016; Wu et al., 2008).
[d] Equipment energy consumption was simulated by ASPEN PLUS 8.4,
[e] Biomass data and assumptions were adopted from Yun's unpublished data (Yu, 2016),
[f] All biomass equipment energy were fully supplied by biochar (Yu, 2016).
[g] Biodiesel HHV data adopted from Mehta et al. (Mehta & Anand, 2009).
[h] Crude glycerol HHV data adopted from Gao et al. (X. Gao et al., 2013).

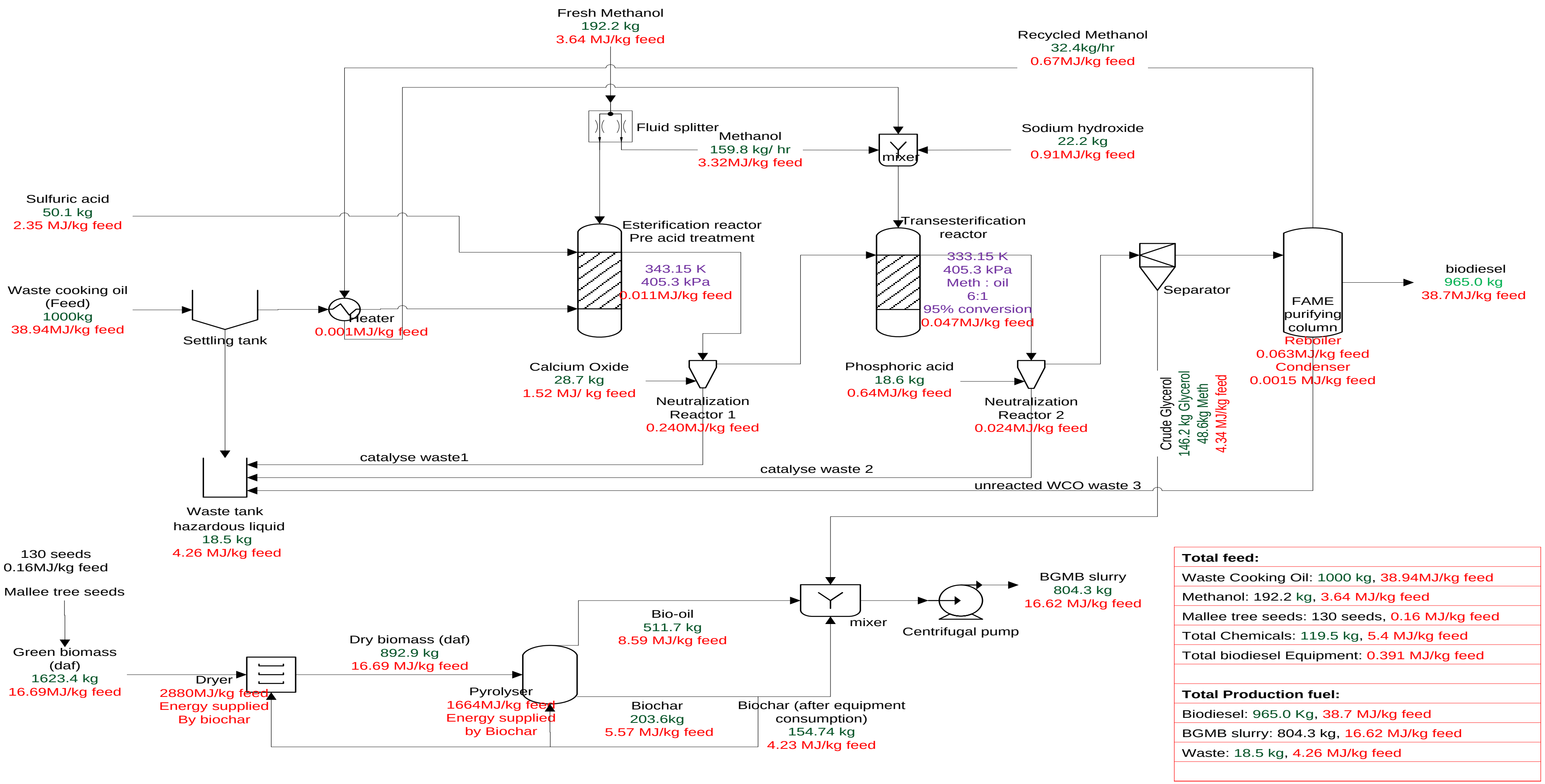

Figure 6-2: Mass and energy balances for the biodiesel-BGB slurry process.

6.6 Functional unit and sub-functional units

The functional unit for the biodiesel-BGB slurry production process is 1 MJ biodiesel, and the by-product is BGB slurry. The sub-functional units of energy and carbon footprints are MJ per MJ biodiesel and kg carbon dioxide equivalent (CO_2-e) per MJ biodiesel respectively.

6.7 Life cycle impact assessment

In this section, high heating values were used for energy analysis (Perry et al., 1997). The equipment efficiency was assumed as 80%. The total amount of energy contained in the biodiesel was set at 38GJ/t (Mehta & Anand, 2009). The glycerol contained energy 0.45GJ/t (X. Gao et al., 2013), and the intermediate by-product biochar contained energy 0.31 GJ/t (Gheorghe et al., 2009).

6.7.1 Life cycle energy impact assessment of biodiesel-BGB slurry process

As mentioned previously in Chapter 4 and 5, the energy inputs of energy balances for the biodiesel from WCO and biomass pyrolysis are 56.99 and 57.35 MJ/kg WCO feed respectively. However, for energy footprint assessment, the energy from WCO itself is assumed as zero because it is a waste in here. Two final products are produced from the biodiesel-BGB slurry process; they are biodiesel and BGB slurry. BGB slurry is a mixture of bio-oil, crude glycerol and biochar. The energy consumptions of the biodiesel-BGB slurry process are relatively low as shown in Table 6-4. The energy ratio is the total outputs of BGB slurry and biodiesel over the total energy input. The result of the energy ratio is similar to the energy ratio of the biodiesel-BMG blend process.

The energy footprint of the biodiesel-BGB slurry process is very similar to the biodiesel-BMG blend process because the remaining biochar from pyrolysis process is completely used in the process. In this process, instead of blending bio-oil, glycerol and methanol into BMG blend, the mixing process takes place by mixing three intermediate by-products: bio-oil, crude glycerol and biochar. Hence, with 1-ton of

WCO feed, the energy footprints of two products – biodiesel and BGB slurry are 122.60 and 44.80 kJ/MJ biodiesel respectively. The overall energy inputs and outputs of biodiesel-BGB slurry process are presented in Table 6-4. The overall detailed life cycle energy impact is shown in Figure 6-3.

The most energy intensive product is biodiesel, 58% and 11% of the total energy input are consumed by methanol and other chemicals in transesterification process respectively. 8% of the total energy input is consumed by utilities during the processes, and 24% of the total energy input is consumed by biomass production from PFT system. Overall, the energy ratio of the biodiesel-slurry process is 8.9, which is similar to the energy ratio of the biodiesel-BMG process.

Table 6-4: Total energy inputs and outputs of the biodiesel-BGB slurry process.

Inputs	**kJ/MJ biodiesel**
Biomass production from PFT system	13.36
Electricity of esterification process	9.12
Chemicals	17.15
Methanol	92.74
Biodiesel distribution	3.08
Pyrolysis process	0.00
Total	**154.4**
Outputs	**kJ/MJ biodiesel**
Biodiesel	1000.00
BGB slurry	421.06
Total	**1421.06**

6.7.2 Life cycle carbon impact of biodiesel-BGB slurry process

As mentioned in Chapters 4 and 5, the average of mallee tree yield is 19.0 dt/ha (Richard J. Harper et al., 2014) and only 892.9kg of biomass is needed for blending in this biofuel process. That means only less than 5% of biomass is employed for the further process, and the rest of the biomass is assumed to be stored on the farm. Finally, 511.7 kg of bio-oil and the remaining 154.74 kg of biochar from the pyrolysis process are mixed with 194.8 kg of crude glycerol to produce 804.3 kg of BGB slurry.

The overall GHG emissions are shown in Figure 6-4. The GHG emissions of the biodiesel-BGB slurry process are similar to the biodiesel-BMG blend process. The total GHG emission of biodiesel-BGB slurry process is 74.1 gCO_2-e/MJ biodiesel including the carbon sequestration in LULUC sector. 62.24 gCO_2-e/MJ biodiesel is allocated to biodiesel and 10.49 gCO_2-e/MJ biodiesel is allocated to the co-product BGB slurry. The first and second largest GHG emission sectors are 37.14 and 18.39 g CO_2-e /MJ biodiesel from transesterification process heat electricity and chemicals respectively. As shown in Figure 6-4, the GHG emission in the pyrolysis process from biomass section is less than 0.01 g CO_2-e/MJ biodiesel. The carbon sequestration is -0.01 g CO_2-e /MJ biodiesel from LULUC. As mentioned in Section 5.9.2.1, the GHG emissions from WCO collection are 0.04 g CO_2-e/MJ biodiesel, i.e. mainly from fuel and oil. This amount of GHG emission is less than 1% of total GHG emissions in the biodiesel-BMG blend process. The savings on carbon footprint from carbon sequestration are too little; hence, the overall carbon footprint savings should focus on replacing the process heat and electricity by green energy to gain credits.

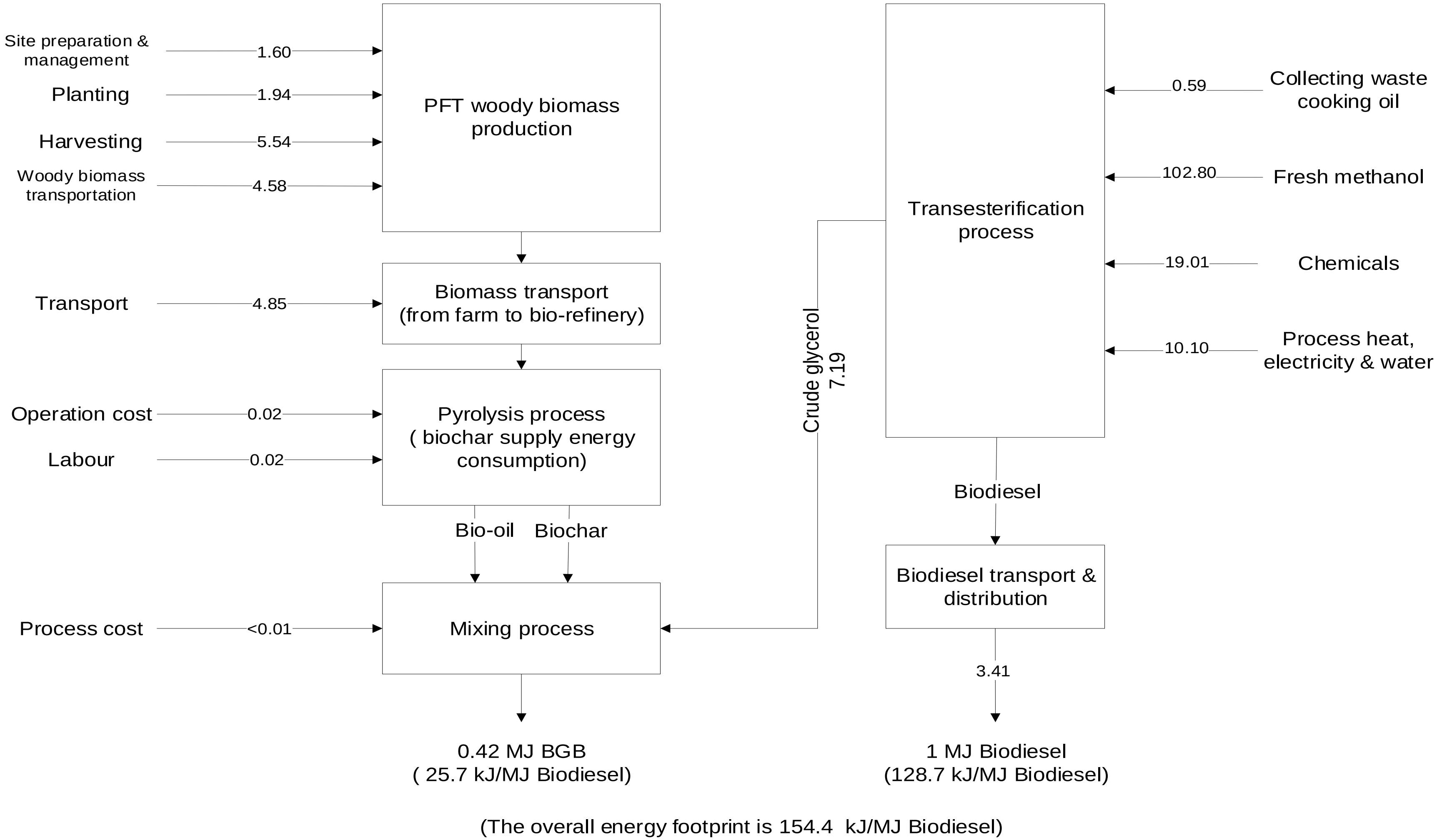

Figure 6-3: Energy footprint of biodiesel-BGB slurry process (the unit of all numbers is kJ/MJ biodiesel)

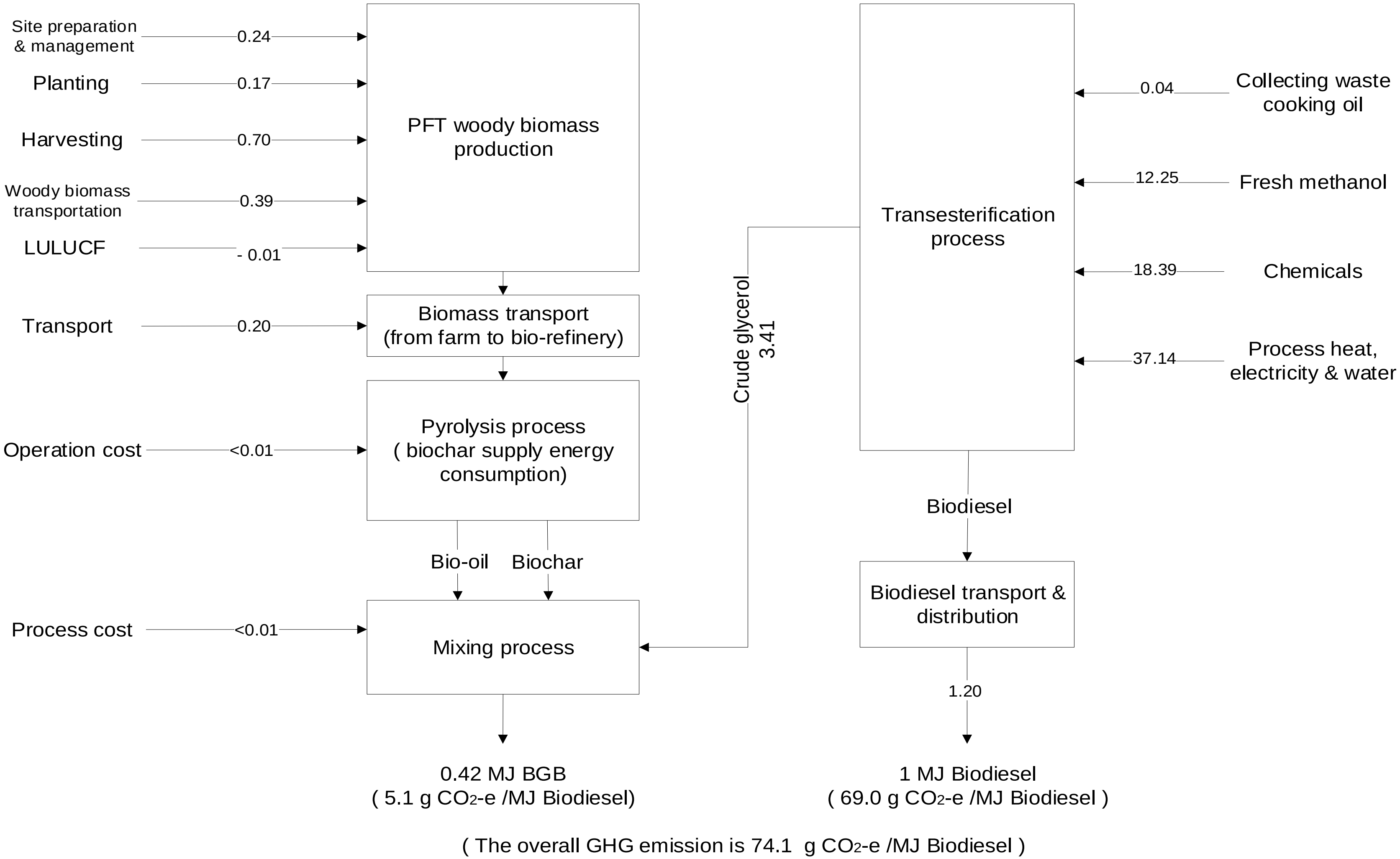

Figure 6-4: Carbon footprints of the biodiesel-BGB slurry process (all unit of the numbers are g CO_2-e/MJ biodiesel)

6.7.3 Comparison with footprints of two biofuel processes

In the biodiesel-BMG process, the total GHG emissions of the biodiesel from WCO process is 69.02 g CO_2-e /MJ biodiesel including the crude glycerol. As discussed in Chapter 5, the GHG emission from WCO collection is 0.04 g CO_2-e /MJ biodiesel, mainly from fuel and oil. This amount of GHG emission is less than 1% of total GHG emissions in the biodiesel process. The total GHG emission from the transport sector is 2.20 g CO_2-e /MJ biodiesel. This is nearly 4% of the total GHG emissions in the biodiesel process. The biodiesel-BMG process proposed different approach to environmental impact by applying biochar as a soil amendment. After the first part of the biochar is consumed for pyrolysis heating process, the rest of biochar (i.e. 155 kg) is applied into soil as a soil amendment. This sequestrates 12.63 g CO_2-e/MJ biodiesel of the process. The total GHG emissions of the biodiesel-BMG process is 55.7 g CO_2-e /MJ biodiesel excluding carbon sequestration from reforest plantation, and the carbon sequestration is only 0.01 g CO_2-e /MJ biodiesel from LULUC sector. This is a trivial amount carbon sequestrated into the soil but the scald land is corrected by plantation. Utilising biochar as fertiliser contributes -12.63 g CO_2-e /MJ biodiesel in the process, which means 16% of the total carbon emissions is sequestrated into soil.

The total GHG emission of the biodiesel-BGB process is 74.1 g CO_2-e/MJ biodiesel. Same as the biodiesel-BMG blend process, the carbon sequestration is -0.01 g CO_2-e /MJ biodiesel from LULUC sector, but biochar is used for form a new fuel instead put it into the soil. The GHG emission from biodiesel transesterification process is 62.24 g CO_2-e/MJ biodiesel, i.e. mainly from chemicals and energy consumptions of the equipment. This amount of GHG emission is more than 90% of the total GHG emissions in the biodiesel process.

The savings on carbon footprint from carbon sequestration in those two processes are very promising from re-forest or agroforest activities. In addition, the scald land correcting means more than just carbon sequestration. From this aspect, the biodiesel-BMG process is more attractive than the biodiesel-BGB process.

6.8 Production cost analysis of biodiesel-BGB slurry process

6.8.1 BGB slurry value evaluation

Bioslurry is a mixture of bio-oil, biochar and glycerol. Bioslurry can be used as a liquid fuel that suits stationary applications such as combustion and gasification.(Abdullah & Wu, 2011) Bioslurry also can be used as feed of biogas gasification process. In this study, bioslurry is a mixture of crude glycerol, bio-oil and biochar. The BGB slurry is the only by-product of the process and it is an important factor in the business sustainability assessment.

There is a same problem in the BMG blend economic assessment, whereby the BGB slurry does not have any market value as it is a new type of fuel. Nevertheless, the market value can be predicted by looking at the relationship between HHV and the fuel's market value. Table 6-5 has shown the relations between HHV and the market price, and the predicted BGB slurry price was $0.399 / kg. It is similar to the BMG blend value ($0.378/kg) due to similar HHV value.

Table 6-5: BGB slurry fuel price prediction

	HHV(MJ/kg)	Price ($/kg)
Diesel	45.76[a]	1.181[c]
Biodiesel	40.16 [a]	0.664 [c]
Gasonline	46.52 [a]	1.504 [c]
Methanol	22.88 [a]	0.406 [d]
BGM blend (predicted)	19.08 [e]	0.378*
BGB slurry (predicted)	20.26[b]	0.399 *

[a] Data are adapted from U.S Department of Energy website (U.S.Department of Energy, 2016) [b]Data were adapted from Gao's publication (W. Gao et al., 2016) [c] The retail prices are adapted from government annual study(*Pump Prices (Retail)*, 2016) [d] The retail price is adapted from the website (Altona Energy, 2013) [e] Data were adapted from Zhang's publication (M. Zhang, 2015b) *Calculated data

6.8.2 Pump selection considerations

In slurry pump applications, the pumps typically have larger size and lower rotational speed than water pumps because the pump speed is limited by the wear life, which decreases as speed is increased. In practice, pump selection needs to consider the slurry concentration and particle size that caused reduction in the theoretical head, efficiency and NPSH characteristics. Wilson and co-workers specified that if the slurry contains high concentration (40% by volume) of large particle size (i.e. 1000 μm or greater solids at high heads 60 meters), then the pump wear cannot be ignored (Wilson, Addie, Sellgren, & Clift, 2006). In this study, the particle sizes of the biochar are less than 75 μm and the concentration of the solid is less than 20wt%. In addition, Gao and co-workers have concluded that BGB slurry generally exhibit non-Newtonian and thixotropic behaviour (W. Gao et al., 2016). Therefore, the slower-running pumps with larger diameter are selected in this study. This type of pump generally is inexpensive. In addition, this plant is designed to operate continuously for 330 days per year; hence the downtime costs are applicable.

Based on all above considerations, there are two pumps running in series with lower specific speed are chosen in the layout of the process in this study.

6.8.3 Comparison with production costs of three biofuel processes

The comparison is deemed necessary since all the biofuels are produced for similar purposes (i.e. renewable fuels) and therefore a feasibility assessment is needed to decide which fuel is more feasible to produce. It is also noteworthy that the BMG blend and BGB slurry have not yet entered the market and the comparison made in this study is based on theoretical values.

As shown in Table 6-6, the capital cost, the raw material and other variable costs (such as transportation, administration and management cost) of the biodiesel-BGB slurry process are less than 5% greater than the biodiesel-BMG blend process. This is due to the capital cost of two pumps in the BGB slurry process. Nevertheless, the BMG blend and BGB slurry processes gain 16% credits in comparison with the traditional biodiesel process costs. The results of the economic assessments have shown the importance of by-product utilisation strategy in biodiesel industry.

Table 6-6: Comparison of production costs of three biofuel processes

Production costs at York town	Biodiesel from WCO process	Biodiesel-BGM blend process	Biodiesel-BGB slurry process
Total capital investment			
Total equipment cost ($)	4021826	4482300	4582300
Permanent investment capital ($)	1693600	1693600	1693600
Working capital ($)	8187400	8186600	8186600
Sub-total A	13902826	14362500	14462500
Annual variable costs			
Raw materials ($)	3276529	5575400	5575400
Utilities ($)	1994500	1993900	1994900
Transport cost($)	1527400	1527400	1527400
Admin other expenses ($)	3827300	3827300	3827300
Management incentives($)	708800	708800	708800
Sub-total B	11334529	13632800	13633800
Annual fixed costs			
Operations ($)	595000	595199	595199
Maintenance ($)	602267	602267	602267
Insurance, taxes($)	116380	116380	116380
Sub-total C	1313647	1313846	1313846
Biodiesel production cost ($/kg)	0.83	0.98	0.98
Crude glycerol credit ($/kg)	-0.11		
Predicted BMG blend credit ($/kg)*		-0.38	
Predicted BGB slurry credit ($/kg)*			-0.40

*Calculated value

6.9 Benchmarking on footprints of biodiesel production and by-product utilisation strategies

A comparison between by-product utilisations and the traditional biodiesel production is shown in Table 6-7. The biodiesel-BGB slurry process has the lowest energy footprint. It is almost halved in comparison to the biodiesel from WCO process. This is due to the BGB slurry gaining 401 kJ/MJ biomass credits and the biomass production requiring less than 1% of the total energy requirement of the process. Compare to the BGB slurry, BGM blend gains 336.39 kJ/MJ biomass credits. The difference in energy gain between the two processes is small. The biodiesel-BGM process has the lowest carbon footprint because the biochar is recycled and used as fertiliser, so this process gains 10.26 g CO_2-e/MJ biomass credit. Furthermore, the total carbon footprint and the cost of the biodiesel-BGM process were reduced by 7 and 20% in compare to the traditional biodiesel process respectively.

6.10 Conclusions

In this chapter, the biodiesel-BGB slurry process was considered and the results have shown the alternative option for the biofuel productions. In summary:

- The biodiesel-BMG blend process performs better economically because both BMG blend and biochar would take more credits than the biodiesel-BGB slurry.
- However, the biodiesel-BGB slurry process is still economically feasible because: (a) the energy ratio was encouraging (8.48), (b) the low capital cost due to the BGB slurry characteristics (i.e. thixotropic behaviour (W. Gao et al., 2016), <20 wt% solid and <70 µm of particle sizes), and (c) low energy and carbon footprints. Moreover, the BGB slurry and the BMG blend have advantages of combustion or gasification because of the methanol present.

Table 6-7: Benchmarking of the life cycle energy and carbon footprints with three biofuel processes

	Biodiesel from WCO process	**Biodiesel-BGM blend process**	**Biodiesel-BGB slurry process**
Energy footprint (kJ/MJ biodiesel)	129.09	160.3	154.4
Farming activities		13.36	13.36
Pyrolysis process		<0.01	<0.01
Biodiesel transesterification process	129.09	122.60	122.60
BGM blending process		57.85	
BGB slurry mixing process			44.80
Crude glycerol energy credit	-110.26		
BGM blend energy credit		-336.39	
BGB slurry energy credit			-421.06
Carbon footprint (g CO_2-e/MJ biodiesel)	69.02	55.7	74.1
Farming activities		3.71	3.71
LULUC credit		-0.01	-0.01
Biochar credit (use as fertiliser)		-12.63	
Pyrolysis process		<0.01	<0.01
Biodiesel transesterification process	69.02	62.24	62.24
BGM blending process		1.61	
BGB slurry mixing process			10.49
Production cost ($/kg)	0.72	0.60	0.58
Biodiesel production cost	0.83	0.98	0.98
Crude glycerol credit	-0.11		
Predicted BMG blend credit		-0.38	
Predicted BGB slurry credit			-0.40

- The results of life cycle assessments have shown similar emissions for both the biodiesel-BGB slurry process and the biodiesel-BMG blend process. By-product utilisation increases financial credits whilst lowering the energy and carbon footprints.

- The biodiesel-BGB slurry process has the lowest energy footprint whilst the biodiesel-BGM blend process has the lowest carbon footprint. However, the biodiesel-BGB slurry process gains the potential environmental credits because of the dust and spontaneous combustion hazards (X. Gao & Wu, 2014; Wu et al., 2010). Therefore, the biodiesel-BGB slurry process should be one of the biofuel options.

Chapter 7 Conclusions and Recommendations

This study has obtained essential knowledge on life cycle assessments for biofuel options in Western Australia. Both biodiesel from waste cooking oil and bio-oil from biomass in phase farm with trees system perform well environmentally and economically. Combining the biodiesel and bio-oil plants would double the benefits and economic performance of the bio-refinery plant.

7.1 Conclusions

- Valley farm system and phase farming with trees system (PFT) are two types of agroforestry configurations that have been recommended since the 1970s. The energy and carbon footprints have been assessed and the positive energy footprint depends on biomass productivities. The PFT system increases the energy productivity from 71.1 to 137.7 GJ/ha-yr and the energy ratio from 3.74 to 26.99. However, from this study, the valley system has shown higher energy efficiency with the productivity of 206 GJ/ha-yr and energy ratio of 41.7.
- Both agro-forestry configurations provide the same opportunities to increase biodiversity and to improve the land condition. This study has shown that the soil orgainc carbon increased by 55% over 10 years during the crop phase but 59% over 5 years during the tree phase. The total GHG emissions for biomass production in the PFT system varied from 1.72 to 6.32 g CO_2-e/MJ biomass for the 5 years production period. With a mean of 19.0 dt/ha biomass productivity, the total GHG emission was 3.05 g CO_2-e/MJ biomass.
- Comparing the energy inputs between PFT and valley system, the annual energy input per ha in the PFT system was 12% higher than the valley system. The biomass crop establishment consumed 32% of the total energy input. The harvesting energy input increased from 26% in PFT to 61% in the valley system because of the intensive harvest activities. Comparing the productivities between those two configurations, the valley system has 14% higher biomass productivity, and so is the energy ratio.

- The water footprint was from 0.13 to 0.06 kL/GJ depending on the plantation density and landscapes. The lower slope and denser plantations provide positive water footprint when compared to the upper slope and sparse plantations.
- The best location of bio-refinery was optimised and York town is found to the best candidate due to its low land cost, relatively short distance (98km) from Perth CBD to the plant and high labour availability.
- With the new biodiesel-BGM blend process, the predicted price of the BGM blend was $0.378/kg. So, the biodiesel production costs will reduce the overall costs by half. Therefore, the gross margin of biodiesel was $0.69/kg which is making this process quite unique and economically sustainable.
- With the new biodiesel-BGB slurry process, the predicted price of the BGB slurry is similar to the BGM blend ($0.399/kg). The economic performance of this process is also similar to the biodiesel-BGM blend process. However, the biodiesel-BGB slurry process reduces the potential environmental hazards from the dust and the spontaneous combustion.
- Compare those three biofuel processes, the biodiesel transesterification process has the lowest energy footprint (129.09 kJ/MJ biodiesel), the biodiesel-BGB slurry process has the lower energy footprint (154.40 kJ/MJ biomass) compare to the biodiesel-BMG blend process, whilst the biodiesel-BGM blend process has the lowest carbon footprint (55.7 g CO_2-e/MJ biomass).

7.2 Recommendations

Developing techno-environmental-economic models for the assessment of bio-refinery is still in its infancy. Long-term optimal use of biomass and other forms of renewable energy are for fuels and the chemical production should be encouraged by government, social media and institutions. Through the best efforts of this study, we make the following recommendations:

- From this study, utilising the by-products (i.e. biochar, crude glycerol) has become the main driving force to commercialise the biodiesel and bio-oil pyrolysis process. More utilisation of by-products should be developed to gain more credits.

- On average, 1.5 tons of crop residues are generated from processing 1 tons of agricultural products. Thus, utilising agricultural biomass wastes will be an interesting waste-to-fuel opportunity in the agro-forestry industry.
- From the water footprint perspective, highly dense plantation at lower slope is better than lowly dense plantation at upper slope in reforest management. Arranging the livestock, pasture and agro-forest in one land should be investigated to utilise the farmland efficiently without sacrificing the environmental benefits.
- The application of fertiliser was assumed to be used in the establishment stage and only once during the production period for both systems, with the additional fertilizer application to compensate for the nutrients that are exported from the soil to mallee biomass. However, this leads to an increase in the total GHG emissions. Some literatures have found that fertilizer application was not necessary in the forest industry, except at the crop establishment stage of the infertile land. Optimising the fertiliser application in forest industry warrants further studies to balance out between high productivities and low GHG emissions.
- This study has demonstrated that forests should be seen as ecological assets. Reforesting in saline land does not only decrease the level of greenhouse gases in the atmosphere also increase the soil organic carbon to slow erosion. Forest or reforest activates should incorporate into agriculture strategies to guarantee the resilience of Australian ecosystems.

References

Abdullah, H., Mourant, D., Li, C.-Z., & Wu, H. (2010). Bioslurry as a Fuel. 3. Fuel and Rheological Properties of Bioslurry Prepared from the Bio-oil and Biochar of Mallee Biomass Fast Pyrolysis. *Energy & Fuels, 24*(10), 5669-5676. doi:10.1021/ef1008117

Abdullah, H., & Wu, H. (2011). Bioslurry as a Fuel. 4. Preparation of Bioslurry Fuels from Biochar and the Bio-oil-Rich Fractions after Bio-oil/Biodiesel Extraction. *Energy & Fuels, 25*(4), 1759-1771. doi:10.1021/ef101535e

AEMO. (2013). *100 Percent Renwables Study - Modelling Outcomes*. Retrieved from AEMO: https://www.environment.gov.au/system/files/resources/d67797b7-d563-427f-84eb-c3bb69e34073/files/100-percent-renewables-study-modelling-outcomes-report.pdf

AgriFutures Austrlia. (2014). Biomass Producer: Bioenergy information for Australia's primary industries. Retrieved from http://biomassproducer.com.au/producing-biomass/biomass-types/tree-residue/samwill-residue/#.U8ZFsZSSzNh

Al-Najar, H. (2011). The Integration of FAO-CropWat Model and GIS Techniques for Estimating Irrigation Water Requirement and Its Application in the Gaza Strip. *Natural Resources, 2011*(2), 8. doi:10.4236/nr.2011.23020

Alexander, E. M., & McDonough, R. C. (2002). Exploration and Production Economics. Retrieved from http://www.pir.sa.gov.au/__data/assets/pdf_file/0020/27335/vol3-12.pdf

Allan, J. A. (1998). Virtual water: A strategic resource. *Ground Water, 36*(4), 545-546. http://dx.doi.org/10.1111/j.1745-6584.1998.tb02825.x

Ally, J., Pryor, T., & Pigneri, A. (2015). The role of hydrogen in Australia's transport energy mix. *International Journal of Hydrogen Energy, 40*(13), 4426-4441. doi:http://dx.doi.org/10.1016/j.ijhydene.2015.02.022

Altona Energy. (2013). Australia: Altona Energy announces results of Arckaringa coal to methanol technical feasibility study. Retrieved from http://www.energy-pedia.com/news/australia/new-155666

Anuar, M. R., & Abdullah, A. Z. (2016). Challenges in biodiesel industry with regards to feedstock, environmental, social and sustainability issues: A critical review. *Renewable and Sustainable Energy Reviews, 58*, 208-223. doi:http://dx.doi.org/10.1016/j.rser.2015.12.296

Aspentech. (2016). Aspen Plus V8.4. Retrieved from http://www.aspentech.com/products/engineering/aspen-plus/whats-new/

Australia Bureau of Statistics. (2010). *1370.0-Measures of Autralia's Progress, 2010*. Canberra: Australia Bureau of Statistics Retrieved from www.abs.gov.au/ausstats/abs@.nsf/Lookup/by%20Subject/1370.0~2010~Chapter~Salinity%20(6.2.4.4).

Australia Bureau of Statistics. (2011). *4630.0 - Agricultural Resource Management Practices, Australia, 2011-12*. Retrieved from Canberra: http://www.abs.gov.au/ausstats/abs@.nsf/Latestproducts/4630.0Main%20Features32011-12?opendocument&tabname=Summary&prodno=4630.0&issue=2011-12&num=&view=

Australian Bureau of Statisitics. (2013). *8165.0 - Counts of Australian businesses, including Entries and Exits, Jun 2009 to Jun 2013* (cat no 8165.0). Retrieved from https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/8165.0Jun%202009%20to%20Jun%202013?OpenDocument

Australian Bureau of Statistics. (2002). *4615.0 - Salinity on Australian Farms*. Canberra: Australian Bureau of Statistics Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/productsbyCatalogue/E3C62B38C2B153AECA256C8B0081EB9B?OpenDocument.

Australian Bureau of Statistics. (2006). *4613.0 - Australia's Environment: Issues and Trends, 2006* Retrieved from http://www.abs.gov.au/ausstats/abs@.nsf/featurearticlesbytitle/3B0DD93AB123A68BCA257234007B6A2F?OpenDocument

Australian Bureau of Statistics. (2011). *AUSTRALIAN POPULATION GRID 2011*. (1270.0.55.007). Canberra: Australian Bureau of Statistics Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/Latestproducts/1270.0.55.007Main%20Features12011.

Australian Bureau of Statistics. (2012a). *1367.0 - State and Territory Statistical Indicators, 2012* (1367.0). Retrieved from Canberra http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by+Subject/1367.0~2012~Main+Features~Energy+Consumption~6.38

Australian Bureau of Statistics. (2012b). *Australian System of National Accounts, 2011-2012, cat. no. 5204.0* Canberra Australian Bureau Statistics Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/5204.02011-12.

Australian Bureau of Statistics. (2013a). *1301.0 - Year Book Australia, 2012*. Retrieved from Canberra:

Australian Bureau of Statistics. (2013b). *3222.0-Population Projections, Australia, 2012 (base) to 2101*. Canberra: Australian Bureau of Statistics.

Australian Bureau of Statistics. (2016). *4604.0 - Energy Account, Australia, 2013-14*. Retrieved from Canberra http://www.abs.gov.au/ausstats/abs@.nsf/latestProducts/4604.0Media%20Release12013-14

Australian Bureau of Statistics. (2019). 8165.0 - *Counts of Australian Businesses, including Entries and Exits, June 2014 to June 2018*. Retrieved from Canberra https://www.abs.gov.au/ausstats/abs@.nsf/latestProducts/8165.0Media%20Release1June%202014%20to%20June%202018

Australian Government - Department of the Environment. (2015). *Australia's 2030 Emissions Reduction Target* (CC102.0815). Retrieved from Canberra: http://www.environment.gov.au/system/files/resources/f52d7587-8103-49a3-aeb6-651885fa6095/files/summary-australias-2030-emissions-reduction-target.pdf

Australian Renewable Energy Agency. (2013). Australia : Accelerating the Commercialisation of Biofuel Technologies. *MENA Report*.

Austrlian Bureau of Statistics. (2014). *9208.0 - Survey of Motor vehicle Use, Australia, 12 months ended 31 October 2014*. Retrieved from http://www.abs.gov.au/ausstats/abs@.nsf/mf/9208.0

Azad, A. K., Rasul, M. G., Khan, M. M. K., Sharma, S. C., Mofijur, M., & Bhuiya, M. M. K. (2016). Prospects, feedstocks and challenges of biodiesel production from beauty leaf oil and castor oil: A nonedible oil sources in Australia. *Renewable and Sustainable Energy Reviews*, *61*, 302-318. doi:http://dx.doi.org/10.1016/j.rser.2016.04.013

B.May, P.Smethurst, C.Carlyle, D.Mendham, J.Bruce, & C.Baillie. (2009). *Review of fertiliser use in Australian forestry* (PRC072-0708). Retrieved from http://www.fwpa.com.au/images/processing/PRC072-0708_Fertiliser_Review_Research_Report_0.pdf

Ball, A., Ahmad, S., Bernie, K., McCluskey, C., Pham, P., Tisdell, C., . . . Feng, A. (2015). *Australian Energy Update*. Retrieved from Canberra: http://www.industry.gov.au/Office-of-the-Chief-Economist/Publications/Documents/aes/2015-australian-energy-statistics.pdf

Beer, T., Grant, T., & Campbell, P. K. (2007). *The Greenhouse and Air Quality Emissions of Biodiesel Blends in Australia* (KS54C/1/F2.28). Retrieved from http://www.caltex.com.au/Media%20Items/PressItem.1053.1552.pdf

Bhran, A. A., Shoaib, A. M., & Umana, B. (2016). Optimization of crude oil hydrotreating process as a function of operating conditions: Application of response surface methodology. *Computers & Chemical Engineering*, *89*, 158-165. doi:http://dx.doi.org/10.1016/j.compchemeng.2016.03.026

Bhuiya, M. M. K., Rasul, M. G., Khan, M. M. K., Ashwath, N., & Azad, A. K. (2016). Prospects of 2nd generation biodiesel as a sustainable fuel—Part: 1 selection of feedstocks, oil extraction techniques and conversion technologies. *Renewable and Sustainable Energy Reviews*, *55*, 1109-1128. doi:http://dx.doi.org/10.1016/j.rser.2015.04.163

Biederman, L. A., & Harpole, W. S. (2013). Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *GCB Bioenergy, 5*(2), 202-214. doi:10.1111/gcbb.12037

Biodiesel Magazine (2016) Existing USA plants. Retrieved from http://www.biodieselmagazine.com/plants/listplants/USA/

Bioenergy Australia. (2016). Biodiesel in Australia. Retrieved from http://biofuelsassociation.com.au/biofuels/biodiesel/biodiesel-in-australia/

Biofuel Economy. (2009). In *Biofuels: Securing the Planet's Future Energy Needs* (pp. 305-318). London: Springer London.

Bradley, D., Levin, E., Rodriguez, C., Williard, P. G., Stanton, A., & Socha, A. M. (2016). Equilibrium studies of canola oil transesterification using a sodium glyceroxide catalyst prepared from a biodiesel waste stream. *Fuel Processing Technology, 146*, 70-75. doi:http://dx.doi.org/10.1016/j.fuproc.2016.02.009

Brooks, B. (2013). $45/bbl Bio crude oil puts new fuel on fast track to market. Retrieved from http://www.ai-online.com/Adv/Previous/show_issue.php?id=5593

Bureau of Meteorology. (2014a). *Average annual & monthly evapotranspiration*. Canberra: Bureau of Meteorology / Australian Government Retrieved from http://www.bom.gov.au/jsp/ncc/climate_averages/evapotranspiration/index.jsp.

Bureau of Meteorology. (2014b). *Twenty-four-monthly rainfall totals for Western Australia*. Canberra: Bureau of Meteorology Retrieved from http://www.bom.gov.au/jsp/awap/rain/index.jsp?colour=colour&time=latest&step=0&map=totals&period=24month&area=nat.

Caldeira, C., Queiros, J., & Freire, F. (2015). Biodiesel from Waste Cooking Oils in Portugal: Alternative Collection Systems. *Waste and Biomass Valorization, 6*(5), 771-779. doi:10.1007/s12649-015-9386-z

Chua, C. B., Hong, Lee, H. M., Low, J. S., & Choong. (2010). Life cycle emissions and energy study of biodiesel derived from waste cooking oil and diesel in Singapore. *The International Journal of Life Cycle Assessment, 15*(4), 417-423. doi:http://dx.doi.org/10.1007/s11367-010-0166-5

Ciriminna, R., Pina, C. D., Rossi, M., & Pagliaro, M. (2014). Understanding the glycerol market. *European Journal of Lipid Science and Technology, 116*(10), 1432-1439. doi:http://dx.doi.org/10.1002/ejlt.201400229

Cleary, S., Bari, M., & Smettem, K. (2009). Targeting Strategic Tree and Perennial Pasture Planting to Reduce Stream Salinity in the Warren River Recovery Catchment. Retrieved from https://www.awa.asn.au/documents/Samuel%20Cleary-OzWater.pdf

Climate Council. (2014). *The Australian Renewable Energy Race: Which states are winning or losing?* Retrieved from http://www.climatecouncil.org.au/uploads/ee2523dc632c9b01df11ecc6e3dd2184.pdf

Climate Council of Australia. (2015). *The Australian Renewable Energy Race: Which States are Wining or Losing?* Retrieved from http://www.climatecouncil.org.au/uploads/ee2523dc632c9b01df11ecc6e3dd2184.pdf

Cunningham, S. C., Mac Nally, R., Baker, P. J., Cavagnaro, T. R., Beringer, J., Thomson, J. R., & Thompson, R. M. (2015). Balancing the environmental benefits of reforestation in agricultural regions. *Perspectives in Plant Ecology, Evolution and Systematics, 17*(4), 301-317. doi:http://dx.doi.org/10.1016/j.ppees.2015.06.001

Csmonitor (2014) How long will world's oil reserves last? 53 years, says BP. https://www.csmonitor.com/Environment/Energy-Voices/2014/0714/How-long-will-world-s-oil-reserves-last-53-years-says-BP

Dale, M. (2007). *Western Australian Government Biofuels Taskforce: Interim Report* Retrieved from

David, A., Winnie, N., & Claire, P. (2010). A Comparison of Biodiesel Processes for the Conversion of Jatropha Curcas, 70. Retrieved from https://www.wpi.edu/Pubs/E-project/Available/E-project-042810-123406/unrestricted/Jatropha_MQP_2010.pdf

De Pontes Souza, D., Mendonça, F. M., Alves Nunes, K. R., & Valle, R. (2012). Environmental and Socioeconomic Analysis of Producing Biodiesel from Used Cooking Oil in Rio de Janeiro. *Journal of Industrial Ecology, 16*(4), 655-664. doi:10.1111/j.1530-9290.2012.00517.x

Department of Agriculture and Food. (2019). Dryland Salinity in Western Australia. Retrieved from https://www.agric.wa.gov.au/soil-salinity/dryland-salinity-western-australia-introduction

Department of Climate Change and Energy Efficiency. (2012). *Australian National Greenhouse Accounts: National Inventory Report 2010 Volume 2*. Retrieved from Canberra: https://www.environment.gov.au/system/files/resources/add6a870-0846-4b62-85ac-78527144e370/files/national-inventory-report-2010-2.pdf

Department of the Environment and Energy (2019), *Australian Energy Update 2019*, Australian Energy Statistics, September, Canberra. Retrieved from https://www.energy.gov.au/sites/default/files/australian_energy_statistics_2019_energy_update_report_september.pdf

Department of the Environment and Energy. 2017b. Australian Energy Update, August 2017. Retrieved from http://www.environment.gov.au/cgi-bin/sprat/public/publicshowcommunity.pl?id=98.

Department of Environment and Climate Change. (2008). book 4 Dryland Salinity: Productive Use of Saline Land and Water Retrieved from http://www.environment.nsw.gov.au/resources/salinity/Book4DrylandSalinity.pdf

Department of Industry and Science. (2015). *Australian Energy Update* Retrieved from Canberra: https://industry.gov.au/Office-of-the-Chief-Economist/Publications/Documents/aes/2015-australian-energy-statistics.pdf

Department of Infrastructure and Regional Development. (2013). *Australian infrastructure statistics-Yearbook 2013* (978-922205-36-0). Canberra: Department of Infrastructure and Regional Development Retrieved from https://www.bitre.gov.au/publications/2013/files/INFRA1886_R_BITRE_INFRASTRUCTURE_YEARBOOK_0813_web.pdf.

Department of Jobs and Small Business. (2019). Agriculture Forestry Fishing *Job Profiles*. Retrieved from https://joboutlook.gov.au/industrySpecific.aspx?industry=A

Department of the Environment. (2017). *Australian National Greenhouse Accounts: Quarterly Update of Australia's National Greenhouse Gas Inventory*. Canbara: Department of the Environment Retrieved from http://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/publications/quarterly-update-australias-national-greenhouse-gas-inventory-dec-2017.

Department of the Environment and energy. (2012). *National Inventory Report 2010 -Volume 3*. Canbara Retrieved from https://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/publications/national-inventory-report-2010.

Department of the Environment and energy. (2013). Land sector reporting - Full Carbon Accounting Model (FullCAM). Retrieved from https://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/land-sector

Dias, G. M., Ayer, N. W., Kariyapperuma, K., Thevathasan, N., Gordon, A., Sidders, D., & Johannesson, G. H. (2017). Life cycle assessment of thermal energy production from short-rotation willow biomass in Southern Ontario, Canada. *Applied Energy, 204*(C), 343-352.

Diya'uddeen, B. H., Abdul Aziz, A. R., Daud, W. M. A. W., & Chakrabarti, M. H. (2012). Performance evaluation of biodiesel from used domestic waste oils: A review. *Process Safety and Environmental Protection, 90*(3), 164-179. doi:http://dx.doi.org/10.1016/j.psep.2012.02.005

Dunn, R. O. (2010). 10 - Other Alternative Diesel Fuels from Vegetable Oils and Animal Fats. In *The Biodiesel Handbook (Second Edition)* (pp. 405-437): AOCS Press.

Economic Development and Infrastructure Committee. (2008). *Inquiry into Mandatory Ethanol and Biofuels Targets in Victoria*. Retrieved from Canberra:

https://apo.org.au/sites/default/files/resource-files/2008/02/apo-nid748-1175666.pdf

Effendi, P., & Courvisanos, J. (2012). Political aspects of innovation: Examining renewable energy in Australia. *Renewable Energy, 38*(1), 245-252. doi:http://dx.doi.org/10.1016/j.renene.2011.07.039

Energy Efficiency & Renewable Energy. (2016). Fuel Prices. Retrieved from https://afdc.energy.gov/

Environmental Audit Committee - Green Economy. (2011). Retrieved from https://www.greengownawards.org/environmental-audit-committee

Written evidence submitted by the UK Sustainable Biodiesel Alliance. (2011). Retrieved from http://www.publications.parliament.uk/pa/cm201012/cmselect/cmenvaud/1025/1025vw08.htm

Farine, D. R., O'Connell, D. A., John Raison, R., May, B. M., O'Connor, M. H., Crawford, D. F., . . . Kriticos, D. (2012). An assessment of biomass for bioelectricity and biofuel, and for greenhouse gas emission reduction in Australia. *GCB Bioenergy, 4*(2), 148-175. doi:10.1111/j.1757-1707.2011.01115.x

Farmwest. (2011). Effective Precipitation. Retrieved from http://www.farmwest.com/node/934

Fassinou, W. F., Sako, A., Fofana, A., Koua, K. B., & Toure, S. (2010). Fatty acids composition as a means to estimate the high heating value (HHV) of vegetable oils and biodiesel fuels. *Energy, 35*(12), 4949-4954. doi:http://dx.doi.org/10.1016/j.energy.2010.08.030

Gallman, P. G. (2011). *Green Alternatives and National Energy Strategy - The Facts behind the headlines*. Baltimore: The Johns Hopkins University Press.

Gan, A. (2015). Asia glycerine market poised to firm on tight supply. Retrieved from https://www.icis.com/explore/resources/news/2015/01/22/9854502/asia-Glycerine-Market-Poised-to-Firm-on-Tight-supply/

Gao, W., Zhang, M., & Wu, H. (2016). Fuel properties and ageing of bioslurry prepared from glycerol/methanol/bio-oil blend and biochar. *Fuel, 176*, 72-77. doi:http://doi.org/10.1016/j.fuel.2016.02.056

Gao, X., Rahim, M. U., Chen, X., & Wu, H. (2017). Inorganic PM10 emission from the combustion of individual mallee components and whole-tree biomass. *Proceedings of the Combustion Institute, 36*(3), 3313-3319. doi:https://doi.org/10.1016/j.proci.2016.08.072

Gao, X., & Wu, H. (2014). Aerodynamic Properties of Biochar Particles: Effect of Grinding and Implications. *Environmental Science & Technology Letters, 1*(1), 60-64. doi:10.1021/ez400165g

Gao, X., Yu, Y., & Wu, H. (2013). Life Cycle Energy and Carbon Footprints of Microalgal Biodiesel Production in Western Australia: A comparison of Byproducts Utilization Strategies. *ACS Sustainable Chemistry & Engineering, 1*(11), 1371. doi:10.1021/sc4002406

Gartner, B. L. (1995). *Plant Stems: Physiology and functional Morphology*. Califormia: Academic Press. Inc.

Gaurav, A., Ng, F. T. T., & Rempel, G. L. (2016). A New Green Process for Biodiesel Production from Waste Oils via Catalytic Distillation using a Solid Acid Catalyst - Modelling, Economic and Environmental Analysis. *Green Energy & Environment*. doi:http://dx.doi.org/10.1016/j.gee.2016.05.003

Geoscience Australia, (2019). Australian Energy Resources Assessment. Retrieved from https://aera.ga.gov.au/

Gheorghe, C., Marculescu, C., Badea, A., Dinca, C., & Apostol, T. (2009). *Effect of Pyrolysis Conditions on Bio-Char Production from Biomass*. Paper presented at the WSEAS Interenational conference. http://www.wseas.us/e-library/conferences/2009/lalaguna/EPREWA/EPREWA32.pdf

Ghezelchi, M. H., Garcia-Perez, M., & Wu, H. (2015). Bioslurry as a Fuel. 7: Spray Characteristics of Bio-Oil and Bioslurry via Impact and Twin-Fluid Atomizers. *Energy & Fuels, 29*(12), 8058-8065. doi:10.1021/acs.energyfuels.5b02089

Gifford, R. M. (1984). Energy in Australian Agriculture: Inputs, Outputs, and Policies. In G. Stanhill (Ed.), *Energy and Agriculture* (pp. 154-168). Berlin, Heidelberg: Springer Berlin Heidelberg.

González-García, S., Berg, S., Feijoo, G., & Moreira, M. T. (2009). Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies. *The International Journal of Life Cycle Assessment, 14*(4), 340-353. doi:10.1007/s11367-009-0089-1

Govement of Western Australia: Office of Energy. (2011). *Strategic Energy Initiative - Directions paper : a smarter energy future for Western Australia*. Retrieved from Perth: http://www.parliament.wa.gov.au/publications/tabledpapers.nsf/displaypaper/3813100cb1e5bc616f7914cc48257855000f71a1/$file/3100-15.03.11.pdf

Government of Western Australia: Department of Housing. (2014). Land and Housing Developments. Retrieved from http://www.landport.com.au

Guo, L. B., & Gifford, R. M. (2002). Soil Carbon Stocks and Land Use Change: a Meta Analysis. *Global Change Biology. Bioenergy, 8*(4), 345.

Hamblin, A., & Derrick, J. (2001). *Land*. Retrieved from Canberra: www.environment.gov.au/node/21737

Harper, R. J. (2014). *Corrigin-NMM*. field work. School of Veterinary and Life Sciences. Murdoch University.

Harper, R. J., Beck, A. C., Ritson, P., Hill, M. J., Mitchell, C. D., Barrett, D. J., . . . Mann, S. S. (2007). The potential of greenhouse sinks to underwrite improved land management. *Ecological Engineering, 29*(4), 329-341. doi:http://dx.doi.org/10.1016/j.ecoleng.2006.09.025

Harper, R. J., Sochacki, S. J., Smettem, K. R. J., & Robinson, N. (2014). Managing water in agricultural landscapes with short-rotation biomass plantations. *Global Change Biology. Bioenergy, 6*(5), 544-555. doi:http://dx.doi.org/10.1111/gcbb.12090

Harris, J. M., & Feriz, M. B. (2011). *Forests, Agriculture, and climate: Economics and Policy Issues*. Retrieved from MA: http://www.ase.tufts.edu/gdae/education_materials/modules/REDD.pdf

ICIS. (2015). Indicative Chemical Prices A-Z. Retrieved from www.icis.com/chemicals/channel-info-chemicals-a-z/

International, O. T. (2010). *Life Cycle Impact of Soybean Production and Soy Industrial Products*. Retrieved from U.S.A: http://biodiesel.org/reports/20100201_gen-422.pdf

International Standard Organization. (1997). ISO 14010:1997, Environmental Management - Life cycle assessment - Principles and framework. In.

IPCC. (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. In *Agriculture, forestry and Other Land Use*. Kanagawa Japan: Intergovernmental Panel on Climate Change (IPCC)

Jayasinghe, s. (2016). Update on U.S. Biomass-Based Diesel Productino and the D4 RINs Market. Retrieved from http://www.agmrc.org/renewable-energy/renewable-energy-climate-change-report/renewable-energy-climate-change-report/may-2016-report/update-on-us-biomass-based-diesel-production-and-the-d4-rins-market/

Jiang, Y., & Zhang, Y. (2016). Supply Chain Optimization of Biodiesel Produced from Waste Cooking Oil. *Transportation Research Procedia, 12*, 938-949. doi:http://dx.doi.org/10.1016/j.trpro.2016.02.045

Jirka, S., & Tomlinson, T. (2014). *2013 State of the Biochar Industry : A Survey of Commercial Activity in the Biochar Field*. Retrieved from http://www.biochar-international.org/sites/default/files/State_of_the_Biochar_Industry_2013.pdf

Keenan, R. J., Parsons, M., A.Gerrand, E.O'Loughlin, Beavis, S., Gunawardana, D., . . . A, B. (2004). *Plantations and water use [electronic resource] : a review prepared for the Forest and Wood Products Research and Development Corporation*. Canberra, A. C. T: Bureau of Rural Sciences.

Krutof, A., & Hawboldt, K. (2016). Blends of pyrolysis oil, petroleum, and other bio-based fuels: A review. *Renewable and Sustainable Energy Reviews, 59*, 406-419. doi:http://dx.doi.org/10.1016/j.rser.2015.12.304

Latitude and Longitude of a Point. (2012). Retrieved from http://itouchmap.com/latlong.htmlS

Lazarus, W., & Selley, R. (2005). *Farm Machinery Economic Cost Estimates for Late 2005*. Retrieved from http://morgan.osu.edu/clark/topics/agriculture-and-natural-resources/farm-management-items/05%20Custom%20Rates.pdf

Lazarus, W., & Selley, R. (2009). Machinery Cost Estimates Retrieved from http://www.extension.umn.edu/agbusinessmanagement/components/pdfs/mf2009.pdf

Lewis, D. (2015). *Project report: Advancing Established and Integrated Marine Microaglae Biofuel to Commercialisation* Retrieved from http://arena.gov.au/files/2015/12/Muradel-final-report.pdf

Li, H., Niu, S., Lu, C., & Li, J. (2016). Calcium oxide functionalized with strontium as heterogeneous transesterification catalyst for biodiesel production. *Fuel, 176*, 63-71. doi:http://dx.doi.org/10.1016/j.fuel.2016.02.067

Liang, S., Liu, Z., Xu, M., & Zhang, T. (2013). Waste oil derived biofuels in China bring brightness for global GHG mitigation. *Bioresource Technology, 131*, 139-145. doi:http://dx.doi.org/10.1016/j.biortech.2012.12.008

Ling, D., Duan, Z., Zhang, X., & Zhu, J. (2013). Research on The Effectiveness of Logistics Performance Assessment. *IFAC Proceedings Volumes, 46*(24), 48-52. doi:http://dx.doi.org/10.3182/20130911-3-BR-3021.00043

Liu, C., Kroeze, C., Hoekstra, A. Y., & Gerbens-Leenes, W. (2012). Past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to major world rivers. *Ecological Indicators, 18*, 42-49. doi:http://dx.doi.org/10.1016/j.ecolind.2011.10.005

Liu, Y., Lu, H., Ampong-Nyarko, K., MacDonald, T., Tavlarides, L. L., Liu, S., & Liang, B. (2016). Kinetic studies on biodiesel production using a trace acid catalyst. *Catalysis Today, 264*, 55-62. doi:http://dx.doi.org/10.1016/j.cattod.2015.07.004

MAHB. (2019) When fossil fuels run out, what then? https://mahb.stanford.edu/library-item/fossil-fuels-run/

Mainroads. (2013). Distance from Perth. Retrieved from www.mainroads.wa.gov.au

Mandil, C. (2016). *biofuels for Transport: An International Perspective*: International Energy Agency.

Marcar, N. E., & Crawford, D. F. (2004). Trees for saline landscapes / by N.E. Marcar and D. F. Crawford. *Canberra, A.C.T: Rural Industries Research and Development Corporation, 2004. ix, 235 pp.*, 2-ix, 235.

Markey, A., & Watson, C. (2011). Australia becomes fast food nation and moves to 11th position for spending on takeaway. Retrieved from http://www.news.com.au/national/obesity-levels-show-australia-is-the-chubby-country/story-e6frfkvr-1226064083008

Mayer, X., Ruprecht, J., & Bari, M. (2005). *Stream Salinity Status and Trends in South-West Western Australia*. (SLUI 38). Canbarra.

McGrath, J. F., Goss, K. F., Brown, M. W., Bartle, J. R., & Abadi, A. (2016). Aviation biofuel from integrated woody biomass in southern Australia. *Wiley Interdisciplinary Reviews: Energy and Environment*, n/a-n/a. doi:10.1002/wene.221

Mehta, P. S., & Anand, K. (2009). Estimation of a Lower Heating Value of Vegetable Oil and Biodiesel Fuel. *American Chemical Society, 23*(8), 5.

Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences, 15*(5), 1577-1600.

Methanol Institute. Methanol Price and Supply / Demand. Retrieved from https://www.methanol.org/methanol-price-supply-demand/

Mettler, M. S., Vlachos, D. G., & Dauenhauer, P. J. (2012). Top ten fundamental challenges of biomass pyrolysis for biofuels. *Energy & Environmental Science, 5*(7), 7797-7809. doi:10.1039/C2EE21679E

Mikkola, H. J., & Ahokas, J. (2010). Indirect energy input of agricultural machinery in bioenergy production. *Renewable Energy, 35*(1), 23-28.

Mohammadshirazi, A., Akram, A., Rafiee, S., & Bagheri Kalhor, E. (2014). Energy and cost analyses of biodiesel production from waste cooking oil. *Renewable and Sustainable Energy Reviews, 33*, 44-49. doi:http://dx.doi.org/10.1016/j.rser.2014.01.067

Morais, S., Mata, T. M., Martins, A. A., Pinto, G. A., & Costa, C. A. V. (2010). Simulation and Life Cycle Assessment of Process Design Alternatives for Biodiesel Production from Waste Vegetable Oils. *Journal of Cleaner Production, 18*, 1251 - 1259.

National Water Commission. (2005). *Australian Water Resources 2005: Water availability*. Retrieved from Canberra: http://www.bom.gov.au/water/awra/AWR2005_Level_2_Report_May07-Summary-results.pdf

Network, W. F. (2014). Water Footprint Glossary. Retrieved from WWW.waterfootprint.org/?page=files/Glossary

Nickish, H. (2003). *Profitability Analysis Spreadsheet*. Philadelphia: University of Pernnsylvania

No, S.-Y. (2014). Application of bio-oils from lignocellulosic biomass to transportation, heat and power generation—A review. *Renewable and*

Sustainable Energy Reviews, 40, 1108-1125. doi:http://dx.doi.org/10.1016/j.rser.2014.07.127

Noguera, G., Araujo, S., Hernández, J., Rivas, A., Mendoza, D., & Castellano, O. (2012). A comparative activity study of a new ultra-dispersed catalyst system for a hydrocracking/hydrotreating technology using vacuum residue oil: Merey/Mesa. *Chemical Engineering Research and Design, 90*(11), 1979-1988. doi:http://dx.doi.org/10.1016/j.cherd.2012.04.006

O'Connell, D. B., David; O'Connor, M. H.; May, Barrie; Raison, R. J.; Keating, Brian A.; Beer, Tom; Braid, A. L.; Haritos, Victoria; Begley, Cameron; Poole, Mick; Poulton, P. L.; Graham, Sonia; Dunlop, Michael; Grant, T.R.; Campbell, Peter; Lamb, David. (2007). *Biofuels in Australia - issues and prospects: A report for the Rural Industries Research and Development Corporation* (1741514681). Retrieved from Canberra:

Ortiz-Martínez, V. M., Salar-García, M. J., Palacios-Nereo, F. J., Olivares-Carrillo, P., Quesada-Medina, J., Ríos, A. P. d. l., & Hernández-Fernández, F. J. (2016). In-depth study of the transesterification reaction of Pongamia pinnata oil for biodiesel production using catalyst-free supercritical methanol process. *The Journal of Supercritical Fluids, 113*, 23-30. doi:http://dx.doi.org/10.1016/j.supflu.2016.03.009

pacific biodiesel. (2016). History of Biodiesel Fuel Retrieved from http://www.biodiesel.com/biodiesel/history/

Panadare, D. C., & Rathod, V. K. (2015). Applications of Waste Cooking Oil other than Biodiesel: A Review. *Iranian Journal of Chemical Engineering, 12*(3), 55.

Papanikolaou, S., Fakas, S., Fick, M., Chevalot, I., Galiotou-Panayotou, M., Komaitis, M., . . . Aggelis, G. (2008). Biotechnological valorisation of raw glycerol discharged after bio-diesel (fatty acid methyl esters) manufacturing process: Production of 1, 3-propanediol, citric acid and single cell oil. *Biomass Bioenergy, 32*. doi:10.1016/j.biombioe.2007.06.007

Patil, P. D., Gude, V. G., Reddy, H. K., Muppaneni, T., & Deng, S. (2012). Biodiesel Production from Waste Cooking Oil Using Sulfuric Acid and Microwave Irradiation Processes. *Journal of Environmental Protection, 3*(1), 107.

Penfold, A. R., & Willis, J. L. (1954). The essential oil industry of Australia. *Economic Botany, 8*(4), 316-336. doi:10.1007/bf02908604

Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., . . . Wagner, F. (2003a). *2003 IPCC: Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Kanagawa: Institute for Global Environmental Strategies (IGES) for the IPCC.

Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., . . . Wagner, F. (2003b). *Good Practice Guidance for Land Use Land-Use Change and Forestry*. Retrieved from Japan: http://www.ipccnggip.iges.or.jp/public/gpglulucf/gpglulucf_files/0_Task1_Cover/Cover_TOC.pdf

Pérez-Fortes, M., Laínez-Aguirre, J. M., Bojarski, A. D., & Puigjaner, L. Optimization of pre-treatment selection for the use of woody waste in co-combustion plants. *Chemical Engineering Research and Design*(0). doi:http://dx.doi.org/10.1016/j.cherd.2014.01.004

Perez, L. L. D. (2015). Outlook '16: US glycerine market faces long supply. Retrieved from http://www.icis.com/resources/news/2015/12/31/9952515/outlook-16-us-glycerine-market-faces-long-supply/

Perry, R. H., Green, D. W., & Maloney, J. O. (1997). *Perry's Chemical Engineering Handbook* (8th ed.).

Pimentel, D., & Burgess, M. (2014). Biofuel production using food. *Environment, Development and Sustainability, 16*(1), 1-3. doi:10.1007/s10668-013-9505-6

Pölczmann, G., Tóth, O., Beck, Á., & Hancsók, J. (2016). Investigation of storage stability of diesel fuels containing biodiesel produced from waste cooking oil. *Journal of Cleaner Production, 111, Part A*, 85-92. doi:http://dx.doi.org/10.1016/j.jclepro.2015.08.035

Productivity Commission of Australia Government. (2013). *Investment and Capacity*. Melbourne Productivity Commission of Australia Government Retrieved from http://pc.gov.au

Pump Prices (Retail). (2016). Retrieved from Canberra: https://aip.com.au/pricing/pump-prices

Pyrolysis char Heating Values. Retrieved from The University of Tennessee of Institute of Agriculture: http://biorefinery.utk.edu/technical_reviews/char%20bio-oil%20HHV.pdf

Waste Reduction and Recycling and Other legislation Amendment Regulation 182 C.F.R. (2013).

Quispe, C. A. G., Coronado, C. J. R., & Carvalho Jr, J. A. (2013). Glycerol: Production, consumption, prices, characterization and new trends in combustion. *Renewable and Sustainable Energy Reviews, 27*, 475-493. doi:http://dx.doi.org/10.1016/j.rser.2013.06.017

Read, V. T. (1988). *Salinity in Western Australia: a situation statement* (81). Retrieved from Perth, Western Australia: https://researchlibrary.agric.wa.gov.au/cgi/viewcontent.cgi?article=1072&context=rmtr

Ritson, P., Clarke, M., Killen, A., & Jeffery, S. (2015). *Testing carbon farming opportunites for salinity managment*. Retrieved from http://www.nacc.com.au/testing-carbon-farming-opportunities-for-salinity-management/

Rodrigues, C. V., Santana, K. O., Nespeca, M. G., Eduardo de Oliveira, J., & Maintinguer, S. I. (2016). Crude glycerol by transesterification process from used cooking oils: Characterization and potentialities on hydrogen bioproduction. *International Journal of Hydrogen Energy, 41*(33), 14641-14651. doi:https://doi.org/10.1016/j.ijhydene.2016.06.209

Rustandi, F., & Wu, H. (2010). Biodiesel Production from Canola in Western Australia: Energy and Carbon Footprints and Land, Water, and Labour Requirements. *Industrial & Engineering Chemistry Research, 49*(22), 11785-11796. doi:10.1021/ie1013162

S.Mani, Sokhansanj, S., X.Bi, & A.Turhollow. (2006). Economics of producing Fuel pellets from biomass. *Applied enegineering in agriculture, 22*(3), 6. doi:10.13031/2013.20447

Schirmer, J., & Field, J. (2010). *The Cost of Revegetation*. Retrieved from Canberra: http://www.environment.gov.au/land/publications/costrev.html

Scott, K. (2013). Biodiesel fuel helping to drive Indigenous engagement in the Pibara. Retrieved from http://www.compass-group.com.au/news/media-centre

Seider, W. D., Seader, J. D., Lewin, D. R., & Widagdo, S. (2009). *Product and Process Design Principles* (third edition ed.). Danvers: Donald Fowley.

Shahiduzzaman, M., & Layton, A. (2015). Decomposition analysis to examine Australia's 2030 GHGs emissions target: How hard will it be to achieve? *Economic Analysis and Policy, 48*, 25-34. doi:http://dx.doi.org/10.1016/j.eap.2015.10.003

Sharifzadeh, M., Wang, L., & Shah, N. (2015). Integrated biorefineries: CO2 utilization for maximum biomass conversion. *Renewable and Sustainable Energy Reviews, 47*, 151-161. doi:http://dx.doi.org/10.1016/j.rser.2015.03.001

Shaw, R., Gordon, I., & Witney, e. (2011). *Salinity management handbook*. (28823). Qeensland: National Library of Australia Retrieved from https://publications.qld.gov.au/dataset/salinity-management-handbook.

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., & Shapouri, H. (1998). *An Overview of Biodiesel and Petroleum Diesel Life Cycles*. (NREL/TP-580-24772).

Sheinbaum-Pardo, C., Calderón-Irazoque, A., & Ramírez-Suárez, M. (2013). Potential of biodiesel from waste cooking oil in Mexico. *Biomass and Bioenergy, 56*(0), 230-238. doi:http://dx.doi.org/10.1016/j.biombioe.2013.05.008

Sheng, C., & Azevedo, J. L. T. (2005). Estimating the higher heating value of biomass fuels from basic analysis data. *Biomass and Bioenergy, 28*(5), 499-507. doi:https://doi.org/10.1016/j.biombioe.2004.11.008

Singhabhandha, A., Kurosawa, M., & Tezuka, T. (2006). *Life Cycle Analysis of Biodiesel Fuel Production : Case study of Using Used Cooking Oil as a Raw*

Material in Kyoto, Japan. Paper presented at the Sustainable Energy and Environment (SEE 2006), Thailand. http://www.jgsee.kmutt.ac.th/see1/cd/file/E-057.pdf

Small Business Development Corporation. (2016). Feasibility of your business idea. *business topics*. Retrieved from https://www.smallbusiness.wa.gov.au/business-topics/starting-a-business/feasibility-of-the-business-idea/

Smorgon group. n.d., Coverting Oils Into Biodiesel. Retrieved from http://www.energyandresources.vic.gov.au/energy/sustainable-energy/bioenergy/converting-oils-into-biodiesel

Sochacki, S. J., Harper, R. J., & Smettem, K. R. J. (2012). Bio-mitigation of carbon following afforestation of abandoned salinized farmland. *GCB Bioenergy*, *4*(2), 193-201. doi:10.1111/j.1757-1707.2011.01139.x

Sonne, E. (2006). Greenhouse Gas Emissions from Forestry Operations. *Journal of Environmental Quality*, *35*, 1439-1450. doi:10.2134/jeq2005.0159

Spencer, B., J. Bartle, D. Huxtable, R. Mazanec, A. Abadi, M. Gibberd, A. Zerihun, A decadal multi-site study of the effects of frequency and season of harvest on biomass production from mallee eucalypts, For. Ecol. Manage. 453 (2019) 117576. doi:10.1016/j.foreco.2019.117576.

Spriggs, E. (2013, 2013 Mar 27). Turning waste food and used cooking oil into power; Food waste and cow dung is being turned into biogas in a move which could help power households in small rural and regional communities. *ABC Premium News*. Retrieved from http://link.library.curtin.edu.au/openurl??url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:journal&genre=unknown&sid=ProQ:ProQ%3Aanznews&atitle=Turning+waste+food+and+used+cooking+oil+into+power%3B+Food+waste+and+cow+dung+is+being+turned+into+biogas+in+a+move+which+could+help+power+households+in+small+rural+and+regional+communities.&title=ABC+Premium+News&issn=&date=2013-03-27&volume=&issue=&spage=&au=Spriggs%2C+Ebonnie&isbn=&jtitle=ABC+Premium+News&btitle=&rft_id=info:eric/&rft_id=info:doi/

Sullivan, R. F., Boduszynski, M. M., & Fetzer, J. C. (1989). Molecular transformations in hydrotreating and hydrocracking. *Energy & Fuels*, *3*(5), 603-612. doi:10.1021/ef00017a013

SunSirs-China Commodity DATA group. (2016). SunSirs Commodity Data Group. Retrieved from www.SUNSIRS.COM

Takle, E., & Hofstrand, D. (2008). Global warming - agriculture's impact on greenhouse gas emissions. *Ag Decision Maker: An agricutural economics and business website*. Retrieved from extension.iastate.edu/agdm/articles/others/TakApr08.html

Talens Peiró, L., Lombardi, L., Villalba Méndez, G., & Gabarrell i Durany, X. (2010). Life cycle assessment (LCA) and exergetic life cycle assessment (ELCA) of the production of biodiesel from used cooking oil (UCO). *Energy, 35*(2), 889-893. doi:http://dx.doi.org/10.1016/j.energy.2009.07.013

Teng, W. K., Ngoh, G. C., Yusoff, R., & Aroua, M. K. (2016). Microwave-assisted transesterification of industrial grade crude glycerol for the production of glycerol carbonate. *Chemical Engineering Journal, 284*, 469-477. doi:http://dx.doi.org/10.1016/j.cej.2015.08.108

Thamsiriroj, T., & Murphy, J. D. (2010). How much of the target for biofuels can be met by biodiesel generated from residues in Ireland? *Fuel, 89*(11), 3579-3589. doi:http://dx.doi.org/10.1016/j.fuel.2010.06.009

Tiwari, R., Rana, B. S., Kumar, R., Verma, D., Kumar, R., Joshi, R. K., . . . Sinha, A. K. (2011). Hydrotreating and hydrocracking catalysts for processing of waste soya-oil and refinery-oil mixtures. *Catalysis Communications, 12*(6), 559-562. doi:http://dx.doi.org/10.1016/j.catcom.2010.12.008

Topp, V., Soames, L., Parham, D., & Bloch, H. (2008). *Productivity in the Mining Industry: Measurement and Interpretation*. Camberra: Australian Government Productivity Commission Retrieved from http://www.pc.gov.au/research/staff-working/mining-productivity.

Tran, T. T. V., Kaiprommarat, S., Kongparakul, S., Reubroycharoen, P., Guan, G., Nguyen, M. H., & Samart, C. Green biodiesel production from waste cooking oil using an environmentally benign acid catalyst. *Waste Management*. doi:http://dx.doi.org/10.1016/j.wasman.2016.03.053

Tyner, W. (2015). Will low oil prices be the downfall of cellulosic biofuels? . Retrieved from http://theconversation.com/will-low-oil-prices-be-the-downfall-of-cellulosic-biofuels-37088

U.S.Department of Energy. (2016). Lower and Higher Heating Values of Fuels. Retrieved from http://hydrogen.pnl.gov/tools/lower-and-higher-heating-values-fuels

U.S.Energy Information Administration. (2016). Gasoline and Diesel Fuel Update. Retrieved from http://www.eia.gov/petroleum/gasdiesel/

Urbanspoon Perth. (2012). Retrieved from http://www.urbanspoon.com/c/338/Perth-restaurants.html

Valente, C., Spinelli, R., Hillring, B. G., & Solberg, B. (2014). Mountain forest wood fuel supply chains: comparative studies between Norway and Italy. *Biomass and Bioenergy, 71*, 370-380. doi:https://doi.org/10.1016/j.biombioe.2014.09.018

Waisel, y., Eshel, A., & Kafkafi, U. (2005). *Plant Roots: The Hidden Half* (third ed.). New York: Taylor & Francies

Wang, M. (2012). GREET LIFE-CYCLE MODEL Available from Transportation Technology R&D Center, from Argonne National Laboratory http://greet.es.anl.gov/

Wang, P. (2000). *Copenhagen Accord*. Canberra Retrieved from http://unfccc.int/meetings/copenhagen_dec_2009/items/5264.php.

Watson, R., Noble, I., Bolin, B., N.H. Ravindranath (India), D. V. U., Ken Andrasko (USA), M. A. C., Sandra Brown (USA), Graham Farquhar (Australia), Donald Goldberg (USA),, Steven Hamburg (USA), R. H. U., Paul Jarvis (UK), Timo Karjalainen (Finland), Haroon Kheshgi (USA),, . . . Raman Sukumar (India), a. R. V. I. (2016). *Land Use, Land-Use Change, and Forestry : A special report of the Intergovernmental Panel on Climate Change*. Retrieved from USA: https://www.ipcc.ch/pdf/special-reports/spm/srl-en.pdf

Weiss, P., Freibauer, A., Gensior, A., Hart, K., Korder, N., Moosmann, L., . . . Schwarzl, B. (2015). *Guidance on reporting and accounting for cropland and grassland management in accordance with Article 3(2) of EU Decision 529/2013/EU - Task 3 of a study for DG Climate Action - LULUCF implementation: guidelines and policy options* (CLIMA.A2/2013/AF3338). Retrieved from London: file:///C:/Users/Lan%20Zhen%20Wang/Downloads/LULUCF_Guidance_on_CM_and_GM.pdf

Wilson, K. C., Addie, G. R., Sellgren, A., & Clift, R. (2006). Pump Selection and Cost Considerations. In K. C. Wilson, G. R. Addie, A. Sellgren, & R. Clift (Eds.), *Slurry Transport Using Centrifugal Pumps* (pp. 338-352). Boston, MA: Springer US.

Wright, A. (2007). *Australian Commodities March Quarter 07.1*. Retrieved from http://adl.brs.gov.au/data/warehouse/pe_abare99001733/ac07_Mar_a5.pdf

Wright, M. M., Satrio, J. A., Brown, R. C., Daugaard, D. E., & Hsu, D. D. (2010). *Techno-Economic Analysis of Biomass Fast Pyrolysis to Transportatoin Fuels*. Retrieved from Colorada:

Wu, H., Fu, Q., Giles, R., & Bartle, J. (2008). Production of Mallee Biomass in Western Australia: Energy Balance Analysis *Energy & Fuels, 22*, 190-198.

Wu, H., Yu, Y., & Yip, K. (2010). Bioslurry as a Fuel. 1. Viability of a Bioslurry-Based Bioenergy Supply Chain for Mallee Biomass in Western Australia. *Energy & Fuels, 24*(10), 5652-5659. doi:10.1021/ef1008105

Y.Hoekstra, A., K.Chapagain, A., M.Aldaya, M., & M.Mekonnen, M. (2011). *The Water Footprint Assessment Manual: Setting the Global Standard*: Earthscan.

Yang, Z., Kumar, A., & Huhnke, R. L. (2015). Review of recent developments to improve storage and transportation stability of bio-oil. *Renewable and Sustainable Energy Reviews, 50*, 859-870. doi:http://dx.doi.org/10.1016/j.rser.2015.05.025

Yu, Y. (2016). *Energy flow of transport fuels production for senario B (two-step refining)*. Chemical Engineering Curtin University.

Yu, Y., Bartle, J., Li, C.-z., & Wu, H. (2009). Mallee Biomass as a Key Bioenergy source in Western Australia: Importance of Biomass Supply Chain. *American Chemical Society, 23*(6), 9. doi:10.1021/ef900103g

Yu, Y., Bartle, J., Mendham, D., & Wu, H. (2015). Site Variation in Life Cycle Energy and Carbon Footprints of Mallee Biomass Production in Western Australia. *Energy & Fuels, 29*(6), 3748-3752. doi:10.1021/acs.energyfuels.5b00618

Yu, Y., & Wu, H. (2010). Bioslurry as a Fuel. 2. Life-Cycle Energy and Carbon Footprints of Bioslurry Fuels from Mallee Biomass in Western Australia. *Energy & Fuels, 24*(10), 5660-5668. doi:10.1021/ef100957a

Zhang, F., Johnson, D. M., & Wang, J. (2015). Life-Cycle Energy and GHG Emissions of Forest Biomass Harvest and Transport for Biofuel Production in Michigan. *Energies, 2015*(8), 3258-3271. doi:10.3390/en8043258

Zhang, H., Wang, Q., & Mortimer, S. R. (2012). Waste cooking oil as an energy resource: Review of Chinese policies. *Renewable and Sustainable Energy Reviews, 16*(7), 5225-5231. doi:http://dx.doi.org/10.1016/j.rser.2012.05.008

Zhang, M. (2015a). *Properties of Bio-oil-Based Fuel Mixtures: Biochar/Bio-oil Slurry Fuels and Glycerol/Bio-oil Fuel Blends.* (Ph.D.), Curtin University, Australia.

Zhang, M. (2015b). *Properties of Bio-oil-Based Fuel Mixtures: Biochar/Bio-oil Slurry Fuels and Glycerol/Bio-oil Fuel Blends.* (PhD), Curtin University Perth.

Zhang, M., Gao, X., & Wu, H. (2013). A Method for the Quantification of Alkali and Alkaline Earth Metallic Species in Bioslurry Fuels. *Energy & Fuels, 27*(11), 6823-6830. doi:10.1021/ef401632h

Zhang, M., Liaw, S. B., & Wu, H. (2013). Bioslurry as a Fuel. 5. Fuel Properties Evolution and Aging during Bioslurry Storage. *Energy & Fuels, 27*(12), 7560-7568. doi:10.1021/ef401888j

Zhang, M., & Wu, H. (2014). Phase Behavior and Fuel Properties of Bio-Oil/Glycerol/Methanol Blends. *Energy & Fuels, 28*(7), 4650-4656. doi:10.1021/ef501176z