Bioslurry as a Fuel. 2. Life-Cycle Energy and Carbon Footprints of Bioslurry Fuels from Mallee Biomass in Western Australia

ARTICLE *in* ENERGY & FUELS · SEPTEMBER 2010

Impact Factor: 2.79 · DOI: 10.1021/ef100957a

2 AUTHORS:

Yun Yu
Curtin University

Hongwei Wu
Yale University

Energy Fuels **2010**, *24*, 5660–5668 · DOI:10.1021/ef100957a
Published on Web 09/14/2010

energy&fuels
article

Bioslurry as a Fuel. 2. Life-Cycle Energy and Carbon Footprints of Bioslurry Fuels from Mallee Biomass in Western Australia

Yun Yu and Hongwei Wu*

Curtin Centre for Advanced Energy Science and Engineering, Department of Chemical Engineering, Curtin University of Technology, GPO Box U1987, Perth, Western Australia 6845, Australia

Received July 26, 2010. Revised Manuscript Received September 2, 2010

This paper reports a life-cycle assessment on energy and carbon footprints of bio-oil/char slurry (i.e., bioslurry) fuel from mallee in Western Australia (WA). The results demonstrate that bioslurry fuels have small energy and carbon footprints, < 4% and < 3% of the total energy and carbon embedded in the delivered fuels, respectively. The energy consumption and greenhouse gas emissions during the life cycle of these fuels are mainly due to biomass production, harvest, and transport. Considering the carbon sinks because of below-ground biomass and land-use change, the carbon footprints of both biomass and bioslurry fuels are actually negative. While a biomass supply chain delivers biomass fuels with smaller energy and carbon footprints for small bioenergy plants, a bioslurry supply chain achieves better performance for dedicated applications only in large-scale centralized plants situated within a biomass collection area. For co-processing applications in coal-based energy plants distant from the biomass collection area, bioslurry as a fuel achieves more energy savings and carbon benefit at a longer transport distance between the biomass collection area and the coal-based energy plant. However, for both biomass and bioslurry fuels, the energy and carbon footprints are small compared to the embedded energy and carbon in the delivered fuels.

1. Introduction

Biomass is considered to be an important renewable source for securing future energy supply and sustainable development.[1] However, the energy and carbon footprints of a bioenergy system depend upon feedstock, conversion technology, end-use application, system boundaries, etc.[2] Biomass fuels are not always carbon-neutral, and in some cases (e.g., forest biomass), carbon emission is even worse than fossil fuels if carbon-stock change as a result of land-use change is considered.[3] Using a global agricultural model, Searchinger et al.[4] demonstrated that carbon emissions because of land-use change as a result of corn-based ethanol production are nearly doubled over 30 years. From an energy point of view, the production of dedicated energy crops also requires non-renewable energy inputs, directly or indirectly via fertilizer application, harvest, transport, etc.[5] Therefore, biomass and/or biofuels may not be truly carbon-neutral in their life cycle, and it is of critical importance to accurately estimate the life-cycle energy and carbon footprints of these fuels.

In Western Australia (WA), the primary objective of mallee biomass development is for managing serious dryland salinity issues, which threaten food production and sustainability in the "wheatbelt" agricultural areas.[6,7] Therefore, mallee biomass is not a dedicated energy crop but a byproduct. Unlike the forest biomass, the carbon footprint of mallee biomass may be low. The reason is that there is no carbon-stock change for annual crops, such as wheat, because much of the wheat plant materials are retained on site following harvest. The sequestered CO_2 during growth would be released to the atmosphere through degradation. Additionally, mallee biomass only substitutes typically < 10% of agricultural land,[8] and the soil carbon stock is in fact likely to increase when changing the land-use from annual crops, such as wheat, to mallee biomass.[9] Lastly, the decrease in wheat production because of land use by mallee biomass may be at least partially offset by the increase of wheat production as a result of improved dryland salinity control. This means that indirect emissions because of land-use change can be minimized.

However, biomass as a fuel suffers from its bulky, fibrous, high-moisture-content, and low-energy-density nature,[10] leading to high transport costs, poor grindability, and mismatch in fuel properties if co-processed with coal.[11−13] Via pyrolysis,

*To whom correspondence should be addressed. Telephone: +61-8-92667592. Fax: +61-8-92662681. E-mail: h.wu@curtin.edu.au.

(1) International Energy Agency (IEA). *World Energy Outlook 2008*; IEA: Paris, France, 2008.
(2) Cherubini, F.; Bird, N. D.; Cowie, A.; Jungmeier, G.; Schlamadinger, B.; Woess-Gallasch, S. *Resour., Conserv. Recycl.* **2009**, *53*, 434–447.
(3) Johnson, E. *Environ. Impact Assess. Rev.* **2009**, *29*, 165–168.
(4) Searchinger, T.; Heimlich, R.; Houghton, R. A.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T.-H. *Science* **2008**, *319*, 1238–1240.
(5) Wu, H.; Fu, Q.; Giles, R.; Bartle, J. *Energy Fuels* **2008**, *22*, 190–198.
(6) Clarke, C. J.; George, R. J.; Bell, R. W.; Hatton, T. J. *Aust. J. Soil Res.* **2002**, *40*, 93–113.
(7) Cooper, D.; Olsen, G.; Bartle, J. R. *Aust. J. Exp. Agric.* **2005**, *45*, 1369–1388.
(8) Bartle, J. R.; Abadi, A. *Energy Fuels* **2010**, *24*, 2–9.
(9) Eggleston, S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland, 2006; Vol. *4*, Agriculture, Forestry, and Other Land Use.
(10) Abdullah, H.; Wu, H. *Energy Fuels* **2009**, *23*, 4174–4181.
(11) Yu, Y.; Bartle, J.; Li, C. Z.; Wu, H. *Energy Fuels* **2009**, *23*, 3290–3299.
(12) Wu, H.; Yu, Y.; Yip, K. *Energy Fuels* **2010**, DOI: 10.1021/ef1008105.
(13) Abdullah, H.; Mourant, D.; Li, C.; Wu, H. *Energy Fuels* **2010**, DOI: 10.1021/ef1008117.

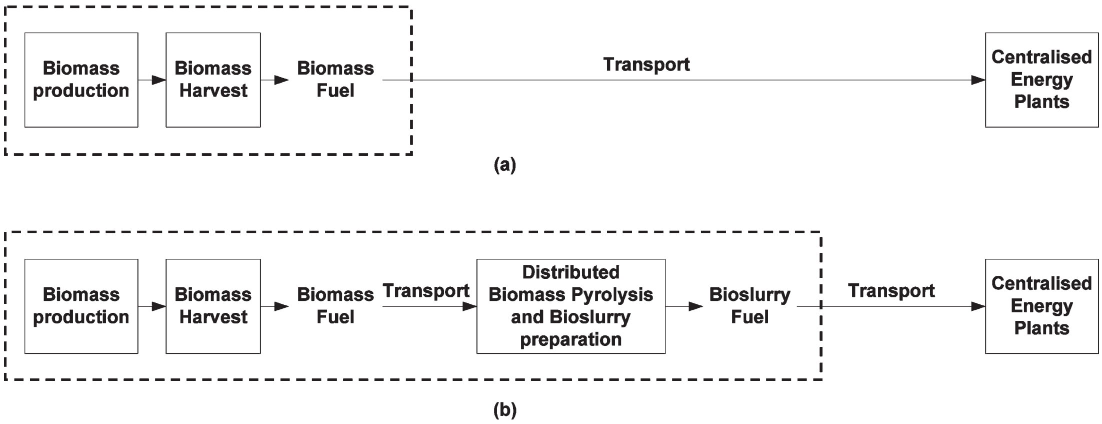

Figure 1. Supply chains of biomass and bioslurry from production to the gate of a processing plant.

biomass can be converted to bio-oil and biochar, with pyrolytic gas being used to supply required process heat. As a result of the excellent biochar grindability,[10] biochar can be easily ground, and the fine biochar particles after grinding can be suspended into the bio-oil to produce a bioslurry fuel, which is of a high volumetric energy density.[12,13] The concept of bioslurry was previously attempted by commercial developers, such as Dynomotive ("BioOil Plus"[14]) and Karlsruhe ("Bioliq"[15]), to reduce transport costs. In fact, besides the advantage of reducing transport costs, bioslurry fuels produced from the distributed pyrolysis plants in local areas where biomass is produced also have little grindability issue (biochar has already been ground) and are a better match with coal for co-combustion/co-gasification.[13] Therefore, preparation and use of bioslurry (or bio-oil/char slurry) fuels is a good strategy to address all of those key issues associated with using biomass as a direct fuel.[12,13] Part 1 (10.1021/ef1008105) of this series has systematically assessed the economic feasibility of a bioslurry supply chain for mallee biomass in WA. The results show that, for dedicated bioenergy plants situated inside the biomass production/collection area, a bioslurry supply chain is only economically competitive at large scales and a small bioenergy plant still favors a biomass supply chain.[12] However, a bioslurry-based supply chain offers significant economic advantages over a biomass supply chain when the energy plant is situated distant from the biomass production/collection area, which is typically the case when biomass is co-processed (e.g., co-fired) in coal-based power stations.

Unfortunately, up to date, no data are available in the published literature on the energy and carbon footprints of bioslurry fuels, while such data are of critical importance to assess the overall sustainability and viability of bioslurry as a fuel. Therefore, it is the objective of this study to carry out a life-cycle assessment (LCA) of energy and carbon footprints of bioslurry fuels from mallee biomass in WA. The results in this study can be used directly as upstream data for the assessment of any downstream or future bioslurry-based processing plants that use mallee-derived bioslurry fuels as feedstock.

2. Methodology

2.1. Overall Considerations. The goal of this LCA is to quantify the energy and carbon footprints of bioslurry fuels from mallee biomass in WA, following the ISO 14040 series guidelines.[16] The overall system consists of biomass production, biomass harvest and transport, bioslurry production, and bioslurry transport to the gate of the bioenergy plant. The life-cycle energy inputs are accounted using higher heating values.[17] The energy and carbon footprints of delivered fuels are then calculated by

$$F_{\text{energy}} = E_{\text{t, HHV}}/E_{\text{fuel, LHV}} \quad (1)$$

$$F_{\text{carbon}} = C_{\text{t}}/E_{\text{fuel, LHV}} \quad (2)$$

where $E_{\text{t,HHV}}$ (MJ) is the life-cycle total energy input on a higher heating value (HHV) basis, $E_{\text{fuel,LHV}}$ (GJ) is the lower heating value (LHV) of the delivered fuel, and C_{t} (kg of CO_2−e) is the life-cycle total greenhouse gas (GHG) emissions. It should be noted that the energy and carbon footprints are based on per unit of useful energy in the fuels (i.e., LHV) delivered to the plant gate. Similar to a previous study,[5] this study also reports the data on energy productivity (MJ ha^{-1} year^{-1}, defined as the total energy output per unit land per year) for both green biomass and bioslurry. The green biomass in this study is defined as the whole-plant chipped mallee biomass particle with a length dimension of ~10 cm and a moisture content of 45%. For carbon footprint analysis, main greenhouse gases (e.g., CO_2, CH_4, and N_2O) were considered in terms of their carbon dioxide equivalent (CO_2−e), which is calculated by multiplying the estimated mass of emissions by the global warming potential.

2.2. Biomass and Bioslurry Supply Chains. As illustrated in Figure 1, this study considers a biomass supply chain (Figure 1a) and a bioslurry supply chain (Figure 1b) from biomass production to the gate of a bioenergy plant. The mallee biomass supply chain is reported in detail elsewhere.[11] It includes biomass production, harvest, on-farm haulage, and road transport and was used in this analysis. This supply chain considers biomass production from mallee grown in the low−medium rainfall (300−600 mm mean annual rainfall) "wheatbelt" agricultural areas of WA by alley farming. Details of the full mallee production system can be found elsewhere.[5] For the purpose of this analysis, the mallee production system has a duration of 50 years, including an initial 5 years to first harvest followed by 15 3-year coppice harvest cycles. The biomass production system is assumed to have an average biomass productivity of 60 green tonnes per hectare per harvest cycle based on the field data in WA. During each harvest, the above-ground biomass of the mallee belts is harvested and chipped to produce biomass in a

(14) Dynamotive BioOil Plus. http://www.dynamotive.com/industrialfuels/biooil_plus/ (accessed on June 19, 2010).
(15) Henrich, E.; Weirich, F. *Environ. Eng. Sci.* **2004**, *21*, 53–64.
(16) International Organization for Standardization (ISO). *ISO 14040−14043, Environmental Management—Life Cycle Assessment*; ISO: Geneva, Switzerland, 1997.
(17) Bossel, U. *Well-to-Wheel Studies, Heating Values, and the Energy Conservation Principle*; European Fuel Cell Forum: Oberrohrdorf, Switzerland, 2003.

flowable form (i.e., biomass particles with a length dimension of ~10 cm). Therefore, chipping is included in the harvest process. On-farm haulage transfers the biomass to a nearby road side for road transport to deliver it to a central processing plant.

For a bioslurry supply chain (see Figure 1b), the system includes additional distributed pyrolysis plants located near the biomass production/collection area. Green biomass is first produced in the field, then harvested (with biomass already chipped into particles with a length dimension of ~10 cm), and transported to distributed pyrolysis plants. The bioslurry produced via the distributed pyrolysis plants will then be transported to a central bioenergy plant. Part 1 (10.1021/ef1008105) of this series[12] has shown that a bioslurry supply chain may exist in two typical scenarios that are considered in this paper. One is the delivery of bioslurry to a dedicated bioenergy plant located within the biomass production/collection area. The other is the delivery of bioslurry to a central processing plant, which is distant from the center of the biomass production/collection area. The second scenario typically represents the delivery of bioslurry fuels to a centralized coal-based energy plant for co-processing, e.g., co-firing of bioslurry fuels in coal-fired power stations.

2.3. Approaches for Assessing Life-Cycle Energy and Carbon Footprints. The LCA exhaustively accounts for all activities and processes that may involve direct (use of agricultural machinery and transport equipment, fertilizer application, etc.) or indirect (production of fertilizers and agrochemicals, production of diesel and petrol fuels, manufacture of agricultural machinery and transport equipment, manufacture of pyrolysis plant construction materials, labor, etc.) energy inputs and GHG emissions during the whole process of the biomass or bioslurry supply chain. This may include production of mallee biomass, biomass harvest and transport, pyrolysis plant construction and operation, and bioslurry preparation and transport. For example, the energy and GHG emissions because of fossil fuel use consider not only direct energy and emissions from vehicles but also those associated with the extraction, production, transport, processing, conversion, and distribution of the fuel. The energy and GHG emissions associated with production, packaging, and delivery of fertilizers and agrochemicals are adapted from the GREET 1.8b model,[18] together with those during the manufacture, maintenance, and disposal of the machinery, including harvesters, tractors, trucks, cars, etc. Monetary costs, such as labor cost, tax, etc., are converted to the energy and GHG emission value using the Australian data on the national average energy consumption and GHG emission per unit gross domestic product.[19]

The energy inputs and GHG emissions during biomass harvest and on-farm haulage are determined by harvester logistics depending upon farm landscape attributes and infrastructure and biomass productivity.[20] The energy and GHG emissions during biomass transport are calculated on the basis of the transport model developed elsewhere.[11] Briefly, the transport logistics were determined on the basis of plant capacity to calculate the required transport equipment. The fuel and labor used were determined on the basis of the road transport distance. The total energy inputs and GHG emissions can then be estimated by considering all of the upstream energy and GHG emissions for transport equipment and fuel and direct energy and GHG emissions during road transport. The energy and GHG emissions during bioslurry transport are estimated in a similar way.

The energy inputs and GHG emissions associated with the construction of distributed pyrolysis plants are estimated from the production and assembly of the construction materials. The amount of materials required was approximated similar to the method used elsewhere.[21−23] The contribution of the plant construction and decommissioning to 1 GJ of bioslurry is calculated on the basis of the bioslurry produced for a plant lifetime of 20 years operating at 330 days per year. The energy and emission for steel, iron, and aluminum were taken from the GREET 2.7 model,[24] while the data for concrete was taken from another reference.[25] The energy and emissions for decommissioning the plant are assumed as 10% of the total construction energy and emissions.[26]

For bioslurry preparation, the biochar particles produced from mallee biomass pyrolysis are ground to fine particles, with 80% less than 75 μm, to facilitate the bioslurry preparation.[13] It is known that bioslurry preparation requires biochar grinding and suspending fine biochar particles into bio-oil; therefore, it is important to estimate the energy inputs and GHG emissions associated with bioslurry preparation. Our previous study showed that, in a laboratory-scale grinder, the grinding of biochar from mallee biomass pyrolysis consumes power similar to Collie coal.[10] Therefore, the data on power consumption of Collie coal grinding in a pilot-scale mill[27] is adapted to estimate the power consumption for biochar grinding. Energy consumption because of power use in mixing biochar and bio-oil for bioslurry preparation is also considered. The analysis also considers the upstream energy and emissions for electricity generation, equipment construction, operation and decommissioning.[18]

The application of nitrogen fertilizers contributes to net GHG emissions of N_2O and CO_2. Detailed emissions in the field vary with and depend upon soil type, climate, crop, tillage method, and fertilizer application rate.[2] The Intergovernmental Panel on Climate Change (IPCC) default method[9] estimates the emissions from several sources, including volatilization of N as NH_3, at a rate of 10% of total N for synthetic N application with 1% conversion to N_2O, direct soil emission of N_2O at 1% for synthetic N application, and runoff/leaching to groundwater as nitrate at 30% of total N applied with 0.75% conversion to N_2O. Therefore, the total emission of N_2O is 1.325% of N in synthetic fertilizer. Because there are insufficient N_2O and CO_2 emission data for fertilizer application in the wheatbelt agricultural area of WA, this study estimates the emissions from a nitrogen fertilizer based on the IPCC guidelines.[9] Both direct and indirect N_2O emissions from fertilizer applications are considered in this analysis.

Land-use change may lead to a variation in soil carbon stock of the land, hence influencing the GHG balance. Globally, soil carbon pool holds 2500 gigatons of carbon, compared to 560 gigatons in vegetation and 760 gigatons in the atmosphere.[28]

(18) Wang, M. *Greehouse Gases, Regulatied Emissions, and Energy Use in Transportation* (*GREET*) *Model, 1.8b*; UChicago Argonne, LLC: Lemont, IL, 2008.

(19) Australian Bureau of Statistics (ABS). *Australian Bureau of Statistics, Energy Use, 1301.0*; ABS: Canberra, Australian Capital Territory (ACT), Australia, 2009.

(20) Giles, R. C.; Harris, H. D. Developing a biomass supply chain for new Australian crops. In *Short Rotation Crops for Bioenergy; Proceedings of the IEA Bioenergy Task 30 Conference*; Tauranga, New Zealand, Dec 1−5, 2003.

(21) Mann, M. K.; Spath, P. L. *Life Cycle Assessment of a Biomass Gasification Combined-Cycle System*; National Renewable Energy Laboratory (NREL): Golden, CO, 1997.

(22) Spath, P. L.; Mann, M. K. *Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System*; National Renewable Energy Laboratory (NREL): Golden, CO, 2000.

(23) Roberts, K. G.; Gloy, B. A.; Joseph, S.; Scott, N. R.; Lehmann, J. *Environ. Sci. Technol.* **2010**, *44*, 827–833.

(24) Wang, M. *Greehouse Gases, Regulatied Emissions, and Energy Use in Transportation* (*GREET*) *Model, 2.7*; UChicago Argonne, LLC: Lemont, IL, 2007.

(25) Sjunnesson, J. Life cycle assessment of concrete. Master's Thesis, Lund University, Lund, Sweden, Sept 2005.

(26) Odeh, N. A.; Cockerill, T. T. *Energy Convers. Manage.* **2008**, *49*, 212–220.

(27) Zulfiquar, M. H.; Moghtaderi, B.; Wall, T. F. *Co-milling of Coal and Biomass in a Pilot-Scale Vertical Spindle Mill*; Technology Assessment Report 49, Cooperative Research Centre for Coal in Sustainable Development (CCSD), University of Newcastle: Newcastle, New South Wales, Australia, March 2006.

(28) Lal, R. *J. Soil Water Conserv.* **2008**, *63*, 113–118.

Table 1. Energy and Carbon Footprints of a Biomass Supply Chain for a Dedicated Plant with a Capacity of 200 Dry Tonnes/Day

	energy footprint[a]			carbon footprint		
	MJ GJ^{-1}	MJ ha^{-1} $year^{-1}$	%	kg of CO_2−e GJ^{-1}	kg of CO_2−e ha^{-1} $year^{-1}$	%
seed	0.2	42	0.9	0.02	4.2	1.0
seedling	0.5	85	1.8	0.05	8.3	2.0
crop establishment	0.4	65	1.3	0.03	5.4	1.3
sapling and coppice management	6.8	1234	25.8	0.7	128.0	30.7
biomass harvest	5.4	978	20.5	0.4	74.9	17.9
biomass on-farm haulage	7.7	1392	29.1	0.6	107.4	25.7
biomass road transport	5.4	981	20.5	0.5	89.1	21.4
total	26.4	4776	100.0	2.3[b]	417.3[b]	100.0
				−15.3[c]	−2771.4[c]	

[a] On a HHV basis. [b] Without considering the carbon sequestrations because of below-ground biomass and land-use change. [c] Considering carbon sequestrations because of below-ground biomass and land-use change.

Dependent upon the previous land use, the soil carbon-stock change can be positive or negative. Because there are no data available on the soil carbon-stock change for converting wheat land for mallee tree plantation, this study adopts the IPCC tier 1 approach and uses the suggested reference carbon stock of 40 tonnes of C ha^{-1} for wheatbelt land in WA.[29]

The CO_2 sequestrated during mallee biomass production includes not only the above-ground biomass (i.e., wood, bark, twig, and leaf) but also the below-ground biomass (i.e., root). The CO_2 sequestrated by above- and below-ground biomass are determined by the carbon contents contained in each mallee biomass component. The yield of above-ground biomass is 60 gigatons per hectare per harvest cycle, with 40% wood, 35% leaf, and 25% bark and twig.[5] Below-ground biomass grows at 25% of total biomass to first harvest.[30] This is a 30% loss of root biomass on harvest, followed by a net 7.5% gain by the following harvest.[8]

3. Results and Discussion

3.1. Energy and Carbon Footprints of Mallee Biomass Fuels. As estimated in Part 1 (10.1021/ef1008105) of this series, the scales of dedicated bioenergy plants using biomass as a direct fuel are fundamentally limited (<500 dry tonnes/day) and such plants favor a biomass supply chain when situated inside the biomass production area.[12] This study first presents the life-cycle energy and carbon footprints of the mallee biomass supply chain for a dedicated bioenergy plant with a typical capacity of 200 dry tonnes/day. It should be noted that our previous studies were carried out to assess the life-cycle energy balance[5] and carbon balance[31] for mallee biomass production, but carbon sequestration by the below-ground root system was not considered. On the basis of a similar supply chain detailed elsewhere,[11] the analysis in this study also accounts for energy inputs on a HHV basis, but comparisons between biomass and bioslurry fuels are based on 1 GJ LHV delivered energy because these fuels have very different moisture contents (~45% for green biomass[5] and ~21% for bioslurry, with a char loading of 20 wt %[13]).

As shown in Table 1, the energy footprint for a biomass supply chain is estimated to be 26.4 MJ GJ^{-1}, which is equivalent to 4776 MJ ha^{-1} $year^{-1}$. Biomass harvest and transport contribute ~70% of total energy inputs. Further analysis to break down the total energy inputs has indicated that total non-renewable energy inputs are dominated by fuel and oil use, fertilizer, and labor use, which account for 46%, 25%, and 17% of total energy inputs, respectively (see Table 2). The energy productivity of a biomass supply chain is estimated to be ~215.6 GJ ha^{-1} $year^{-1}$, which is slightly higher than ~206.3 GJ ha^{-1} $year^{-1}$ in our previous analysis,[5] as results of the small variations in the energy contents of biomass components. Therefore, the energy footprint for a biomass supply chain is very low, only ~2.2% of total energy accumulated in above-ground biomass.

The total GHG emissions for a biomass supply chain are also very small, only ~2.3 kg of CO_2−e GJ^{-1}, equivalent to ~417.3 kg of CO_2−e ha^{-1} $year^{-1}$. The majority of total GHG emissions also arise from biomass harvest and transport. The breakdown of GHG emissions in Table 2 has indicated that total GHG emissions are also dominated by the use of fuels (and oil), fertilizer, and labor, which account for 46%, 25%, and 19% of total GHG emissions, respectively. It should also be noted that such results are obtained from the use of the default IPCC value on the emission factor (1.325%) from the application of N fertilizer. Barton et al.[32] measured the N_2O emission from a rain-fed, cropped soil in a semi-arid region of southwestern Australia for 1 year on a sub-daily basis and found that the emission factor after correction for the background emission (no N fertilizer applied) was only 0.02%, more than 60 times lower than the IPCC default value. This suggested that the analysis in this study is conservative, and the actual total GHG emissions can be even lower.

Two additional factors need to be considered in assessing the life-cycle carbon footprint of biomass and biomass-derived fuels, i.e., carbon sequestration in below-ground biomass (i.e., root system) and carbon sink because of land-use change. Table 3 shows that the carbon sequestrated in above- and below-ground biomass are ~108.8 and ~5.5 kg of CO_2−e GJ^{-1}, respectively. The above-ground biomass will be harvested and used as an energy resource, so that the sequestered carbon will be eventually released to the atmosphere. On the contrary, the below-ground biomass, i.e., the root system of mallee biomass, is not harvested and, hence, makes no contribution to energy output. However, the below-ground biomass retained in the soil offers a dynamic carbon sink. Without considering the carbon sink because of below-ground biomass, the GHG emissions during biomass production are only 2.1% of total carbon sequestered in

(29) *National Inventory Report 2008 Vol. 1−3, Australian National Greenhouse Accounts, the Australian Government Submission to the UN Framework Convention on Climate Change*; Department of Climate Change and Energy Efficiency, Australian Government: Canberra, Australian Capital Territory (ACT), Australia, May 2010.

(30) Sochacki, S. J.; Harper, R. J.; Smetterm, J. R. J.; Wu, H., *Biomass Bioenergy* **2010**, submitted for publication.

(31) Yu, Y.; Bartle, J.; Wu, H. Production of mallee biomass in Western Australia: Life cycle greenhouse emissions. In *Chemeca 2008 Conference*; Newcastle, New South Wales, Australia, Sept 28−Oct 1, 2008.

(32) Barton, L.; Kiese, R.; Gatter, D.; Butterbach-Bahl, K.; Buck, R.; Hinz, C.; Murphy, D. V. *Global Change Biol.* **2008**, *14*, 177–192.

Table 2. Breakdown of Total Energy Inputs and GHG Emissions of a Biomass Supply Chain for a Plant of 200 Dry Tonnes/Day

	energy inputs			GHG emissions		
	MJ GJ^{-1}	MJ ha^{-1} $year^{-1}$	%	kg of CO_2−e GJ^{-1}	kg of CO_2−e ha^{-1} $year^{-1}$	%
fuel and oil use	12.2	2201	46.1	0.9	161.3	38.7
fertilizer application	6.5	1170	24.5	0.7	124.5	29.8
labor use	4.4	798	16.7	0.4	79.3	19.0
machinery use	1.6	286	6.0	0.1	22.9	5.5
seed and seedlings	0.7	127	2.7	0.07	12.5	3.0
agrochemicals	0.3	51	1.1	0.02	2.7	0.7
other operation costs	0.8	142	3.0	0.08	14.1	3.4
total	26.4	4776	100.0	2.3	417.3	100.0

Table 3. Carbon Sequestrations for Mallee Biomass and Bioslurry Fuels

	biomass			bioslurry		
	kg of CO_2−e GJ^{-1}	kg of CO_2−e ha^{-1} $year^{-1}$	%	kg of CO_2−e GJ^{-1}	kg of CO_2−e ha^{-1} $year^{-1}$	%
above-ground biomass (A)[a]	(108.8)	(19694.1)		(116.9)	(19694.1)	
below-ground biomass (B)[b]	5.5	988.7	31.0	5.9	988.7	31.0
land-use change (C)	12.1	2200.0	69.0	13.0	2200.0	69.0
total (B + C)	17.6	3188.7	100.0	18.9	3188.7	100.0

[a] Above-ground biomass delivers energy output, but the carbon embedded will eventually be released after end energy use, so that it is not considered as a carbon sink. [b] Below-ground biomass (i.e., root system) does not deliver energy output, but the carbon sequestrated in the below-ground biomass is a dynamic carbon sink.

above-ground biomass for a plant with a capacity of 200 dry tonnes/day. However, after considering the carbon sink in below-ground biomass, the mallee biomass is in fact carbon-negative, leading to a net reduction in carbon emission of ~3.2 kg of CO_2−e GJ^{-1}.

It is also known that, when a forest is converted to agricultural land, there would be a loss of carbon stock and the carbon stock may increase when trees are planted.[9] Typically, converting cropland to grassland increases soil carbon at rates of 0.2−1.0 tonnes ha^{-1} $year^{-1}$ for several decades.[2] Therefore, the plantation of mallee trees also leads to an increase in carbon stock in soil, further increasing the carbon sequestration and improving the benefits of mallee-based bioenergy. On the basis of the estimation using the IPCC tier 1 approach, the results in Table 3 also show that mallee plantation sequesters an additional ~12.1 kg of CO_2−e GJ^{-1} as a result of land-use change from wheat to mallee. This provides further offset to the GHG emissions during mallee production. Overall, it leads to a negative carbon emission of ~15.3 kg of CO_2−e GJ^{-1}, considering a plant capacity of 200 dry tonnes/day.

3.2. Energy and Carbon Footprints of Bioslurry Fuels from Mallee Biomass for a Centralized Bioenergy Plant Situated within the Biomass Collection Area. Analysis in Part 1 (10.1021/ef1008105)[12] suggests that a bioslurry supply chain can be economically competitive and attractive in two scenarios for mallee biomass in WA. One is the delivery of bioslurry fuels to large-scale bioenergy plants (e.g., > equivalent capacity of 1500 dry tonnes/day) located within the biomass collection area. The other is the delivery of bioslurry for co-processing (e.g., co-firing) with coal in coal-based energy plants situated distant from the biomass collection area. This section discusses energy and carbon footprints of a bioslurry-based supply chain for a dedicated bioenergy plant, benchmarking against a biomass supply chain with the same capacity.

The results are listed in Table 4 for a bioenergy plant with an equivalent capacity of 1500 dry tonnes of biomass/day. It should be noted that a dedicated bioenergy plant based on a biomass chain is fundamentally of a small scale in practice, so that the study on a capacity of 1500 dry tonnes biomass/day based on a biomass supply chain is for comparisons only. As expected, when the green biomass is processed in the distributed pyrolysis plants to produce bioslurry as a fuel, the total energy productivity decreases because any extra step of processing would cost more energy. For example, a bioslurry-based supply chain has the energy productivity of ~186.9 GJ ha^{-1} $year^{-1}$, compared to ~215.6 GJ ha^{-1} $year^{-1}$ for a biomass supply chain. For a dedicated plant to process 1500 dry tons of biomass/day, the energy footprint for a bioslurry-based supply chain is 36.9 MJ GJ^{-1}, a little more than that of 34.8 MJ GJ^{-1} for a biomass supply chain. The energy input contributed by biomass road transport is reduced substantially from ~40% to ~12%. A bioslurry supply chain also introduces additional energy inputs as a result of the construction and operations of distributed pyrolysis plants, as well as bioslurry preparation and transport. Table 4 indicates that such additional energy inputs contribute to ~39% of total non-renewable energy inputs.

Deployment of a bioslurry supply chain for a dedicated plant to process 1500 dry tonnes of biomass/day only leads to a total GHG emission of ~3.3 kg of CO_2−e GJ^{-1}, slightly higher than that of ~3.1 kg of CO_2−e GJ^{-1} for a biomass supply chain. This is equivalent to the annual GHG emissions of ~559 kg of CO_2−e ha^{-1} $year^{-1}$ for a bioslurry supply chain. The majority of GHG emissions arise from biomass production, i.e., sapling and coppice management, on-farm haulage, and harvest. Biomass and bioslurry transports only account for ~12% and ~9% of total GHG emissions, respectively. Therefore, for a centralized large-scale bioenergy plant situated within the biomass collection area, the energy consumptions and GHG emissions are also very low, only 3.3% and 2.8% of total energy and carbon embedded in the delivered bioslurry fuels. Bioslurry fuels may potentially save more energy and reduce more GHG emissions than green biomass, depending upon the trade-off between the reduction in energy consumption and emissions in biomass transport and the increase in those aspects in pyrolysis plant construction and operation and bioslurry preparation and transport.

Table 4. Energy and Carbon Footprints of Mallee Biomass and Bioslurry Produced from 1500 Dry Tonnes/Day

	energy footprint[a]						carbon footprint					
	biomass			bioslurry			biomass			bioslurry		
	MJ GJ^{-1}	MJ ha^{-1} $year^{-1}$	%	MJ GJ^{-1}	MJ ha^{-1} $year^{-1}$	%	kg of CO_2−e GJ^{-1}	kg of CO_2−e ha^{-1} $year^{-1}$	%	kg of CO_2−e GJ^{-1}	kg of CO_2−e ha^{-1} $year^{-1}$	%
seed	0.2	42	0.7	0.2	42	0.7	0.02	4.2	0.8	0.03	4.2	0.7
seedling	0.5	85	1.4	0.5	85	1.4	0.05	8.3	1.5	0.05	8.3	1.5
crop establishment	0.4	64	1.0	0.4	64	1.0	0.03	5.4	1.0	0.03	5.4	1.0
sapling and coppice management	6.8	1234	19.6	7.3	1234	19.8	0.7	128.0	23.1	0.8	128.0	22.9
biomass harvest	5.4	978	15.5	5.8	978	15.7	0.4	74.9	13.5	0.4	74.9	13.4
biomass on-farm haulage	7.7	1391	22.1	8.3	1391	22.3	0.6	107.4	19.4	0.6	107.3	19.2
biomass road transport	13.8	2496	39.7	4.3	730	11.7	1.2	215.8	40.8	0.4	66.4	11.9
pyrolysis plant construction				1.4	241	3.9				0.1	21.8	3.9
pyrolysis plant operation				1.9	321	5.2				0.2	31.8	5.7
bioslurry preparation				3.3	555	8.9				0.4	58.3	10.4
bioslurry transport				3.5	585	9.4				0.3	52.8	9.4
total	34.8	6292	100.0	36.9	6226	100.0	3.1[b] −14.5[c]	544.0[b] −2644.7[c]	100.0	3.3[b] −15.6[c]	559.1[b] −2629.6[c]	100.0

[a] On a HHV basis. [b] Without considering the carbon sequestrations because of below-ground biomass and land-use change. [c] Considering carbon sequestrations because of below-ground biomass and land-use change.

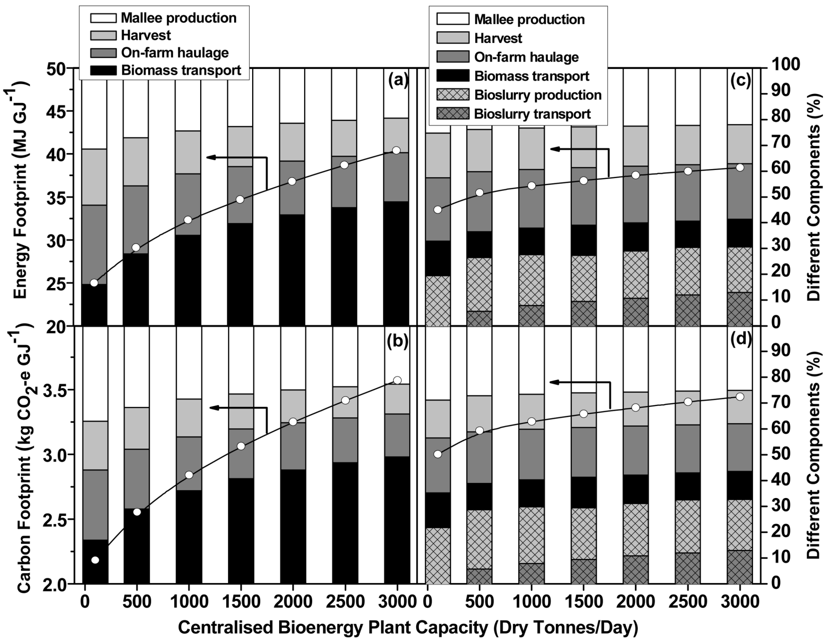

Figure 2. Energy and carbon footprints of biomass and bioslurry and their main components as a function of the plant capacity for a dedicated central plant: (a) energy footprint of biomass, (b) carbon footprint of biomass, without considering carbon sequestrations because of below-ground biomass and land-use change, (c) energy footprint of bioslurry, and (d) carbon footprint of bioslurry, without considering carbon sequestrations because of below-ground biomass and land-use change. Note that bioslurry is produced from the same amount of biomass at an optimal number of distributed pyrolysis plants.

Also, as shown in Table 4, considering carbon sequestration by below-ground biomass and carbon sink because of land-use change, the overall carbon footprint of bioslurry is actually carbon-negative. The carbon footprint of bislurry is −15.6 kg of CO_2−e GJ^{-1}, which is larger than −14.5 kg of CO_2− GJ^{-1} of biomass at the same plant capacity of 1500 dry tons/day. The results show that the increase in total GHG emissions is less than the increase in carbon sequestration, leading to an increase in the overall negative carbon emission for a bioslurry supply chain. As a result, the overall carbon footprint of bioslurry fuels (as negative carbon emission, −15.6 kg of CO_2−e GJ^{-1} at 1500 dry tonnes/day; see Table 4) is even higher than that of green biomass for small bioenergy plants (−15.3 kg of CO_2−e GJ^{-1} at 200 dry tonnes/day; see Table 1).

Further studies were then carried out to investigate the carbon and energy footprints of both biomass and bioslurry supply chains as a function of the centralized bioenergy plant capacity, with the results presented in Figure 2. The carbon footprints of biomass and bioslurry were presented without considering carbon sequestrations because of below-ground biomass and land-use change. At each plant capacity in Figure 2, the number of distributed pyrolysis plants has been optimized to obtain the minimal energy consumption and GHG emissions of bioslurry to the central plant gate. Panels a and c of Figure 2 clearly indicate that, under optimized conditions, the energy footprints of delivered biomass or bioslurry fuels are small although increase with the plant capacity. For example, when the plant capacity increases from 500 to 3000 dry tonnes/day, the energy footprint of biomass increases from ~25 to ~40 MJ GJ^{-1}, while that of bioslurry only increases from ~34 to ~38 MJ GJ^{-1}. However, the energy footprint of bioslurry is considerably less sensitive to the plant capacity in comparison to those of biomass. This is mainly due to the substantial reduction in energy consumption during biomass transport and the optimization of the number of distributed pyrolysis plants in the supply chain. On the basis of our estimation, a bioslurry supply chain leads to a lower energy footprint than a biomass supply chain, when the plant capacity is above 2500 dry tonnes/day. For the carbon footprints of biomass and bioslurry as indicated in panels b and d of Figure 2, they show similar trends as the energy footprints, if the carbon sequestrations because of below-ground biomass and land-use change are not considered. For the plant capacity range of 500−3000 dry tonnes/day, the carbon footprints of biomass and bioslurry are also small and in the range of 2.2−3.6 and 3.0−3.4 kg of CO_2−e GJ^{-1}, respectively. The bioslurry supply chain also leads to a lower carbon footprint than a biomass supply chain with a plant capacity over 2500 dry tonnes/day. If considering the carbon sequestrations, the carbon footprints

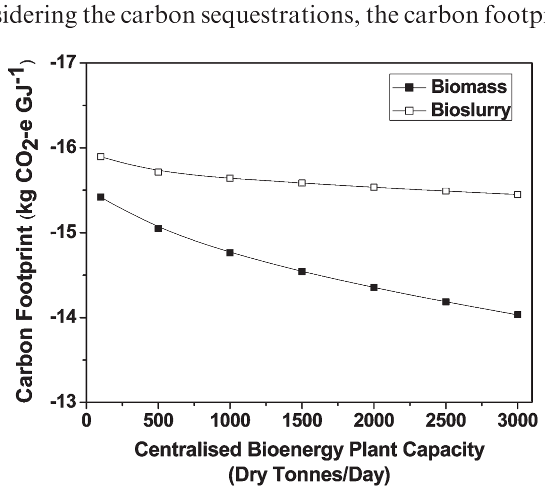

Figure 3. Carbon footprints of biomass and bioslurry as a function of the plant capacity for a dedicated central plant, considering carbon sequestrations because of below-ground biomass and land-use change. Note that bioslurry is produced from the same amount of biomass at an optimal number of distributed pyrolysis plants.

of biomass and bioslurry both show negative emissions and reduce with plant capacity (as negative carbon emission), as presented in Figure 3. However, the bioslurry supply chain always shows higher carbon net emissions than the biomass supply chain, e.g., 15.9−15.4 kg of CO_2−e GJ^{-1} for bioslurry and 15.4−14.0 kg of CO_2−e GJ^{-1} for biomass (as negative carbon emission), for a plant capacity of 100−3000 dry tonnes/day. These data indicate that bioslurry as a fuel shows better performance from the viewpoint of emissions for the dedicated bioenergy plant situated within the biomass collection area.

3.3. Energy and Carbon Footprints of Biomass and Bioslurry Fuels for Co-processing in Coal-Based Energy Plants Situated Distant from the Biomass Collection Area. A bioslurry supply chain offers significant economical competitiveness when the fuels need to be transported distant from the center of the biomass collection area.[12] This typically represents the case where biomass and/or bioslurry is transported to large-scale coal-based energy plants for co-processing (i.e., co-firing) applications. For example, in the wheatbelt area of WA, the most likely co-processing application is the co-firing of mallee biomass produced in the Narrogin area in the Muja coal-fired power station, which is situated in Collie, with a transport distance of ~110 km.

Table 5 presents the results on the energy and carbon footprints of biomass and bioslurry fuels to substitute 5% energy of a 300 MW_e coal-fired power station, with the distance of 100 km between the plant and biomass collection area. The energy footprint of delivered bioslurry is estimated to be 36.2 MJ GJ^{-1}, a significant reduction from 43.6 MJ GJ^{-1} for biomass. Similarly, the total GHG emissions of delivered fuels reduce from ~3.9 to ~3.2 kg of CO_2−e GJ^{-1}, using bioslurry as a fuel instead of biomass. For the energy inputs and GHG emissions of green biomass, more than half are due to biomass road transport. While for bioslurry, the contribution of biomass road transport reduces substantially to be ~10% for both energy inputs and GHG emissions. Contributions of additional bioslurry production and transport are only ~28% of total energy inputs and GHG emissions. The energy consumptions and GHG emissions are also very low, only 3.3% and 2.8% of total energy and carbon embedded in the delivered bioslurry fuels. The data

Table 5. Energy and Carbon Footprints of Mallee Biomass and Bioslurry Production To Substitute 5% Energy of a 300 MW_e Coal-Fired Power Station with the Distance of 100 km from the Biomass Collection Area

	energy footprint[a]						carbon footprint					
	biomass			bioslurry			biomass			bioslurry		
	MJ GJ^{-1}	MJ ha^{-1} $year^{-1}$	%	MJ GJ^{-1}	MJ ha^{-1} $year^{-1}$	%	kg of CO_2−e GJ^{-1}	kg of CO_2−e ha^{-1} $year^{-1}$	%	kg of CO_2−e GJ^{-1}	kg of CO_2−e ha^{-1} $year^{-1}$	%
seed	0.2	42	0.5	0.2	42	0.7	0.02	4.2	0.6	0.03	4.2	0.8
seedling	0.5	85	1.1	0.5	85	1.4	0.05	8.3	1.2	0.05	8.3	1.5
crop establishment	0.4	64	0.8	0.4	64	1.4	0.03	5.4	0.8	0.03	5.4	1.0
sapling and coppice management	6.8	1234	15.6	7.3	1234	20.2	0.7	128.0	18.3	0.8	128.0	23.5
biomass harvest	5.4	978	12.4	5.8	978	16.0	0.4	74.9	10.7	0.4	74.9	13.8
biomass on-farm haulage	7.7	1391	17.6	8.3	1391	22.8	0.6	107.3	15.3	0.6	107.3	19.7
biomass road transport	22.7	4106	52.0	3.7	623	10.2	2.1	371.4	53.1	0.3	56.7	10.4
pyrolysis plant construction				1.7	286	4.7				0.2	25.8	4.8
pyrolysis plant operation				2.2	376	6.2				0.2	37.2	6.8
bioslurry preparation				3.3	555	9.1				0.3	58.3	10.7
bioslurry transport				2.8	467	7.7				0.2	37.7	6.9
total	43.6	7901	100.0	36.2	6100	100.0	3.9[b] −13.7[c]	699.6[b] −2489.1[c]	100.0	3.2[b] −15.7[c]	543.8[b] −2644.9[c]	100.0

[a] On a HHV basis. [b] Without considering the carbon sequestrations because of below-ground biomass and land-use change. [c] Considering carbon sequestrations because of below-ground biomass and land-use change.

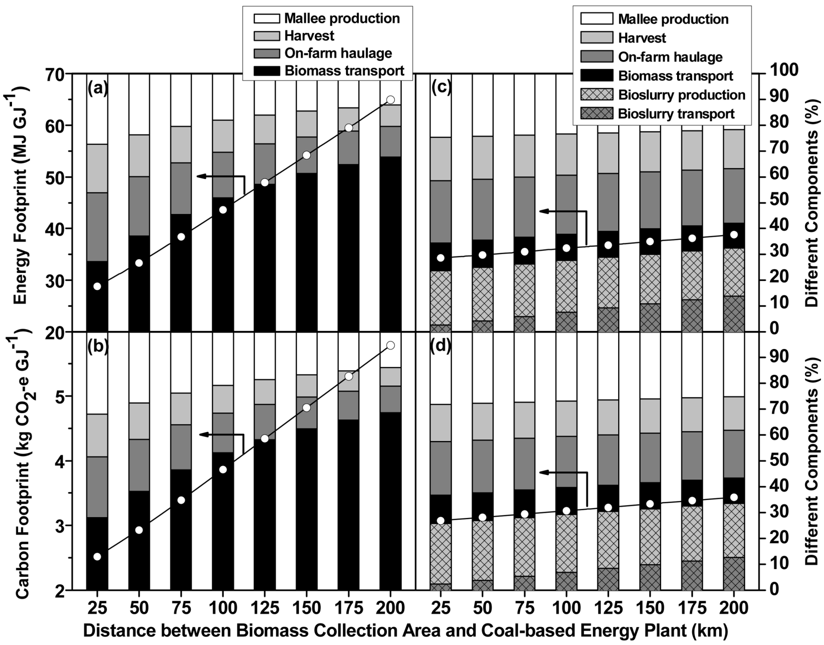

Figure 4. Energy and carbon footprints of biomass and bioslurry and their main components as a function of the distance between the coal-fired plant and biomass collection area to supply 5% energy substitution of a 300 MW_e coal-fired power station: (a) energy footprint of biomass, (b) carbon footprint of biomass, without considering carbon sequestrations because of below-ground biomass and land-use change, (c) energy footprint of bioslurry, and (d) carbon footprint of bioslurry, without considering carbon sequestrations because of below-ground biomass and land-use change. Note that bioslurry is produced from the same amount of biomass at an optimal number of distributed pyrolysis plants.

clearly demonstrate the advantages of a bioslurry supply chain in such a case, while the fuels need to be transported to coal-based energy plants situated distant from the biomass collection area for co-processing applications.

At a distance of 100 km between the coal-fired power station and the biomass collection area, the analysis also shows that the energy inputs and GHG emissions achieve minimum at a total of four distributed pyrolysis plants. Further increasing the pyrolysis plant number will lead to the increase of both energy inputs and GHG emissions (data not shown). While increasing the number of distributed pyrolysis plants can further reduce the energy inputs and GHG emissions from biomass road transport, such a reduction is actually less than the increase in additional energy inputs and GHG emissions because of bioslurry production and transport. The optimal number of distributed pyrolysis plants is therefore determined by the trade-off between these two factors.

For the co-processing application in coal-based energy plants, further evaluation was then carried out to investigate the effect of the distance between the plant and biomass collection area on the life-cycle energy and carbon footprints of biomass and bioslurry fuels. Those data are shown in Figures 4 and 5. Similarly, the carbon footprints of biomass and bioslurry were also presented with and without considering carbon sequestrations because of below-ground biomass and land-use change. Panels a and c of Figure 4 indicate that the energy footprints of delivered biomass or bioslurry fuels all increase with the distance between the plant and biomass collection area. However, the energy footprint of bioslurry is considerably less sensitive to the distance in comparison to those of biomass. For example, to substitute 5% (on the basis of energy) coal use in a 300 MW_e coal-fired power station, the energy footprint for bioslurry increases moderately from 34.9 MJ GJ^{-1} for 50 km to 36.2 MJ GJ^{-1} for 100 km and then to 38.8 MJ GJ^{-1} for 200 km, in

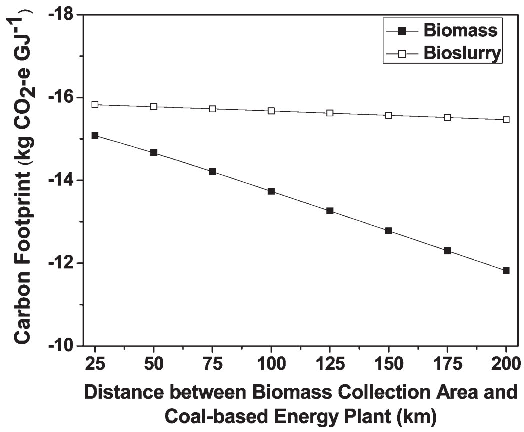

Figure 5. Carbon footprints of biomass and bioslurry as a function of the distance between the coal-fired plant and biomass collection area to supply 5% energy substitution of a 300 MW_e coal-fired power station, considering carbon sequestrations because of below-ground biomass and land-use change. Note that bioslurry is produced from the same amount of biomass at an optimal number of distributed pyrolysis plants.

comparison to 33.3, 43.6, and 64.9 MJ GJ^{-1} for biomass. The energy footprint of bioslurry fuels is less than that of green biomass only when the fuels need to be transported over a minimal distance between biomass collection area and coal-fired power station, e.g., ~65 km for 5% energy substitution. For the carbon footprints of biomass and bioslurry, as indicated in panels b and d of Figure 3, they show similar trends to the energy footprints if the carbon sequestrations because of below-ground biomass and land-use change are not considered. For example, the carbon footprint for bioslurry increases moderately from 3.1 kg of CO_2−e GJ^{-1} for 50 km to 3.2 kg of CO_2−e GJ^{-1} for 100 km and then to 3.4 kg of CO_2−e GJ^{-1} for 200 km, in comparison to 2.9, 3.9, and 5.8 kg of CO_2−e GJ^{-1} for

Table 6. Energy and Carbon Footprints of Bioslurry Production for Co-processing at Various Energy Substitutions and Distances

	energy footprint^a (MJ GJ^{-1})						carbon footprint (kg of CO_2−e GJ^{-1})					
	5%			20%			5%			20%		
	50 km	100 km	200 km	50 km	100 km	200 km	50 km	100 km	200 km	50 km	100 km	200 km
seed			0.2						0.03			
seedling			0.5						0.05			
crop establishment			0.4						0.03			
sapling and coppice management			7.3						0.8			
biomass harvest			5.8						0.4			
biomass on-farm haulage			8.3						0.6			
biomass road transport		3.7			6.4			0.3			0.6	
pyrolysis plant construction		1.7			1.0			0.2			0.1	
pyrolysis plant operation		2.2			1.4			0.2			0.1	
bioslurry preparation		3.3			3.3			0.3			0.3	
bioslurry transport	1.5	2.8	5.4	1.7	2.9	5.4	0.1	0.2	0.4	0.1	0.2	0.4
total	34.9	36.2	38.8	36.2	37.3	39.9	3.1^b −15.8^c	3.2^b −15.7^c	3.4^b −15.5^c	3.2^b −15.7^c	3.3^b −15.6^c	3.5^b −15.4^c

^{a} On a HHV basis. ^{b} Without considering the carbon sequestrations because of below-ground biomass and land-use change. ^{c} Considering carbon sequestrations because of below-ground biomass and land-use change.

biomass. The advantages of a bioslurry supply chain in reducing energy and carbon footprints become more significant as the distance between the biomass collection area and coal-fired power station increases.

Because the bioslurry has the potential to replace considerably more coal use (e.g., 20% energy substitution) during co-firing, analysis was then carried out to investigate the energy inputs and GHG emissions at various bioslurry energy substitutions. As shown in Table 6, it is interesting to see that both the non-renewable energy inputs and GHG emission only slightly increase with the energy substitution. For example, the total energy inputs increase by ~1.1 MJ GJ^{-1}, when increasing the bioslurry energy substitution from 5% to 20% at a distance of 100 km between the plant and biomass collection area, while the total GHG emission is only increased by ~0.1 kg of CO_2−e GJ^{-1}. There results clearly show that, in comparison to a biomass supply chain, a bioslurry-based supply chain offers advantages in increasing energy substitution of coal use, in saving the non-renewable energy inputs and reducing GHG emissions when the distance between the coal energy plant and biomass collection area is over 65 km.

It is also noteworthy that, after considering carbon sequestrations by below-ground biomass and carbon sink because of land-use change, a bioslurry supply chain also delivers an overall negative carbon footprint for co-processing (e.g., co-firing) applications of bioslurry fuels in coal-based energy plants situated distant from the biomass collection area. As shown in Figure 5, it is interesting to see that the bioslurry supply chain always shows a higher overall carbon footprint (as negative carbon emission) than the biomass supply chain, if considering carbon sequestrations. For example, as shown in Table 5, the total carbon footprint for bioslurry is −15.7 kg of CO_2−e GJ^{-1}, in comparison to −13.7 kg of CO_2−e GJ^{-1} for biomass, for a distance of 100 km between the plant and biomass collection area. Furthermore, a significant increase from 5% to 20% in energy substitution in coal use by bioslurry fuels also leads to only slight reduction in net carbon emissions (see Table 6), i.e., from 15.7 to 15.6 kg of CO_2−e GJ^{-1} (as negative carbon emission). These data further demonstrate that bioslurry is also better than biomass from the emission point of view for the bioenergy plant distant from the biomass collection area.

This study has shown that a biomass supply chain delivers biomass fuels with smaller energy and carbon footprints for small dedicated bioenergy plants and a bioslurry supply chain shows better performances for the co-processing in a plant situated distant from the biomass collection area, particularly at a longer transport distance. However, the energy and carbon footprints are small in comparison to the total energy and carbon embedded in the delivered fuels. For example, at a transport distance ranging from 25 to 200 km for co-processing applications in coal-based plants, the energy footprints of biomass and bioslurry are only 2.4−5.4% and 3.1−3.5% of the embedded energy in the delivered fuels, respectively, while their carbon footprints are only 2.3−5.3% and 2.6−2.9% of the carbon in the delivered fuels, respectively.

4. Conclusions

Life-cycle energy and carbon footprints of mallee-derived bioslurry are less than 4% and 3% of total energy and carbon embedded in the delivered bioslurry fuels. When the carbon sinks because of below-ground biomass and land-use change are considered, the carbon footprint becomes carbon-negative. While a biomass supply chain has smaller energy and carbon footprints for small-scale dedicated bioenergy plants, a bioslurry supply chain delivers considerably better performance for co-processing applications in coal-based energy plants situated distant from the biomass collection area, achieving more energy savings and carbon benefits at a longer transport distance from the biomass collection area to coal-based plant. However, for both biomass and bioslurry fuels, the life-cycle energy and carbon footprints are small compared to their embedded energy and carbon in their delivered fuels.

Acknowledgment. Support from Australia's Department of Innovation Industry, Science, and Research through the Australia−China Special Fund for S&T Cooperation (CH070008) is acknowledged.