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Bioslurry as a Fuel. 1. Viability of a Bioslurry-Based Bioenergy Supply Chain for Mallee Biomass in Western Australia

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This paper evaluates the economic feasibility of a bioenergy supply chain based on bioslurry (i.e., bio-oil/char slurry) for mallee biomass in Western Australia (WA). The bioslurry-based supply chain utilizes distributed pyrolysers within the biomass production area, converts the harvested green biomass into bioslurry fuels, and then delivers the bioslurry fuels to a central bioenergy plant. The results show that the overall economic feasibility of such a supply chain depends on the trade-off between the reduction in biomass transport cost and the increase in costs due to the introduction of distributed pyrolysers (including bioslurry preparation) and bioslurry transport. For a dedicated bioenergy plant situated within the biomass production area, a bioslurry-based supply chain is only competitive on a large scale (e.g., $>$1500 dry tonnes per day), and small bioenergy plants (e.g., $<$ 500 dry tonnes per day) still favor a conventional biomass supply chain. However, a bioslurry-based supply chain offers significant advantages in reducing the delivered cost of fuels at the plant gate when the central bioenergy plant is distant from biomass production area. This is the case for cofiring biomass/bioslurry in coal-fired power stations in WA. Bioslurry offers significant advantages to address the key issues associated with biomass utilization, including high transport cost, poor grindability and mismatch in fuel properties if coprocessing with coal. A bioslurry-based supply chain also makes it economically feasible to substantially increase the uptake of bioenergy proportion in coal-fired power stations, e.g., from 5% in a biomass supply chain to 20% in a bioslurry-based bioenergy supply chain.

1. Background

Biomass will be one of the most important renewable energy sources in the future, and its production is under development in many regions of the world.[1−7] In the wheatbelt region of the southwest of Western Australia (WA), mallee eucalypts are being developed as a perennial coppice crop to produce woody biomass. The objective is to integrate mallee cropping into the agricultural system in an "alley farming" configuration (i.e., wide-spaced narrow belts occupying $<$10% of the land). If mallee is commercially viable, it is likely to be adopted on a large scale. Little conflict with food production is likely because of the small proportion of land occupied and also because it would help remedy some entrenched problems in the economic and environmental performance of agriculture in the WA wheatbelt. In particular, it could make a substantial contribution to control of land degradation, especially the pervasive problem of dryland salinity.[5,6] Alley farming of mallee increases yield through better water utilization, and this means the relatively small area planted has the potential to produce commercially important quantities of biomass. Mallee biomass production has high energy efficiency partly because it is a coppicing crop that does not require replanting after harvest.[6,8]

However, biomass production is typically widely dispersed, and biomass as a fuel is bulky and has a high moisture content and low energy density. For example, whole-plant chipped mallee biomass has a particle size with a length dimension of ~10 cm, and it has 45% moisture and a very low volumetric energy density of ~5 GJ/m^3 in comparison to the ~28 GJ/m^3 of typical black coals.[9] Transport will be a large proportion of the total cost of mallee biomass delivered to a bioenergy plant in Western Australia (WA).[10] It is accepted that long-distance transport of biomass will not be feasible.[10−13] This will restrict any dedicated mallee-based bioenergy plant in WA to small capacity.

Since dedicated bioenergy plants will not achieve the economies of scale with much higher efficiencies and availabilities, coprocessing of biomass in large-scale coal-based plants, e.g., cofiring in coal-fired power stations or cogasification in coal-based entrained flow gasifiers, represents the most promising pathway for biomass utilization.[14] Co-processing biomass with coal in large-scale coal-based plants could also

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achieve economies of scale for biomass utilization with much higher efficiencies and availabilities as well as significant reduction in CO_2 and other emissions.[14] The technology can be rapidly adapted into the vast existing coal-based infrastructure. However, biomass has a fibrous nature and poor grindability[14−17] so biomass utilization such as coprocessing would have to overcome the constraint of large biomass particles. A dedicated biomass-based bioenergy plant must be flexible to take large biomass particles. Large-scale coal-based plants typically have ball milling systems that are unsuitable for grinding biomass and consume significant milling power.[15,18−20] Hence, poor grindability of biomass is a key impediment to biomass coprocessing in large-scale coal-based plants.

Conversion of biomass by combustion/gasification is dominated by gaseous phase reactions. This causes problems of mismatch in fuel properties between biomass and coal during coprocessing. For example, when biomass is cofired in existing coal-fired power stations, it generates a large quantity of flue gas. This influences the combustion stability, reduces the residence time of coal/char particles in the boiler, and increases the loss of combustibles, leading to an overall plant efficiency loss.[14,15]

Therefore, efficient and economic utilization of biomass requires innovations to significantly improve volumetric energy densification, biomass grindability, and, if coprocessing with coal, good fuel matching. Several approaches have been developed to improve energy density and/or grindability, including torrefaction, briquetting/pelletizing, and pyrolysis. Torrefaction[21,22] and briquetting/pelletizing[23−26] are light thermal treatment technologies that operate at low temperatures. These technologies largely address the grindability issue and achieve moderate (volumetric) energy densification. In contrast, pyrolysis is a high temperature technology that converts biomass into solid (biochar), liquid (bio-oil), and pyrolytic gas. The light gases can be used to supply the energy for pyrolyser operations. Bio-oil may be further upgraded and refined for the production of liquid transport fuels[27−33] and has a high volumetric energy density to be favorable for transport.[34] Biochar is also an excellent fuel for cofiring in coal-fired power stations due to its excellent grindability, achieving significant volumetric energy densification and favorable particle shapes of fine char particles after grinding.[16,17] However, transport of fine char particles may be dusty and prone to spontaneous combustion.

Transportability and energy density could be enhanced by suspending biochar in bio-oil to produce a bioslurry fuel. This was the concept attempted by commercial developers such as Dynomotive ("BioOil Plus"[35]) and Karlsruhe ("Bioliq"[36]). At present, direct cofiring of biomass as a fuel can only substitute up to 5% of coal (on an energy basis) in coal-fired power stations,[37−39] limited dominantly by the poor grindability of biomass. A bioslurry method may remove this constraint. Our related study has demonstrated that biochar has excellent grindability.[16,17] Therefore, it appears feasible to use bulk harvested biomass as a feedstock for pyrolysers to produce biochar and bio-oil. Instead of consuming substantial energy to achieve size reduction of the biomass particles, the biochar can be easily ground into fine char particles that can then be suspended into bio-oil to make bioslurry fuels. It is also known that cofiring of bio-oil with coal has the potential to substitute a much higher energy ratio of coal.[40] Additionally, a previous study showed the application of biomass-diesel-kerosene slurry fuels in stationary engines.[41] Therefore, besides dedicated bioenergy applications (e.g., gasification[42]), bio-oil/char slurry (i.e., bioslurry) fuels are also may be suitable for cofiring with coal in coal-fired power stations and combustion in stationary engines.

The production of bioslurry fuels requires a system of distributed pyrolysis plants such that a bioslurry supply chain can only be viable when the extra local pyrolysis is offset by the cost savings in transport. Unfortunately, there are few data available on the properties of bioslurry fuels in the literature. A previous economic analysis was conducted on the Karlsruhe biomass-to-liquid process in Europe based on a combination of syngas production from large-scale dedicated "Bioliq" gasification and subsequent liquid fuels production via Fischer−Tropsch synthesis.[42] However, little work has yet been done to assess the feasibility of incorporating bioslurry fuels into the mallee biomass supply chain in WA for dedicated or coprocessing applications.

Therefore, the objectives of this series of papers are to report the results of a systematic study on the economic viability (part 1 of this series), life cycle energy and carbon footprints (part 2 of this series,[43] 10.1021/ef100957a), and fuel and rheological properties (part 3 of this series,[9]10.1021/ef1008117)

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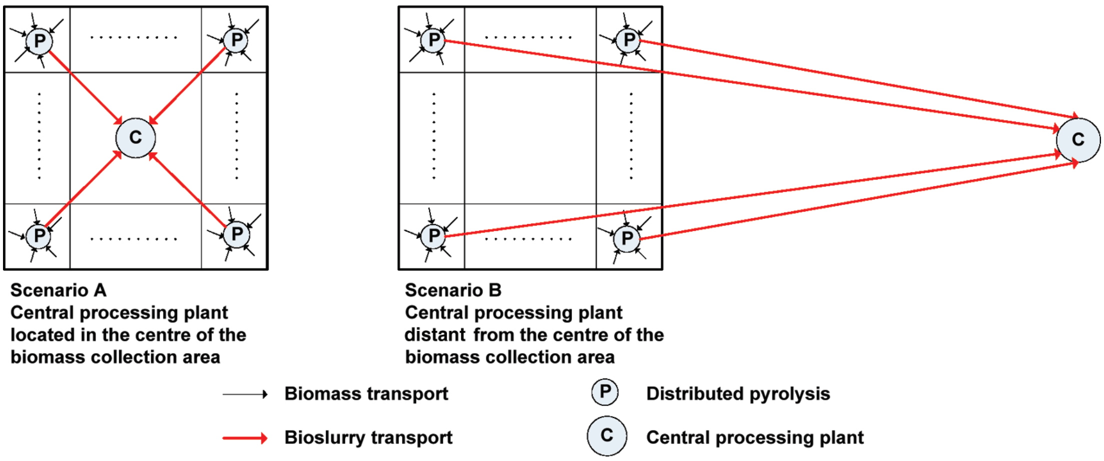

Figure 1. Two different scenarios of supplying bioslurry fuels to a central processing plant. Scenario A: Central processing plant located in the center of the biomass collection area. Scenario B: Central processing plant distant from the center of the biomass collection area.

of bioslurry fuels produced from bio-oil and biochar products of mallee biomass pyrolysis. This paper is part 1 of this series and evaluates the economic feasibility of a bioslurry-based bioenergy supply chain for mallee biomass in WA.

2. Methodology

This study concerns the economic performance of a bioslurry-based bioenergy supply chain for mallee biomass in WA. The results are then benchmarked against a conventional biomass supply chain which was detailed previously.[10] All calculations carried out are based on Australian dollars ($A) with real values in year 2009. In this study, the conventional biomass supply chain is adapted to incorporate the pyrolysis and bioslurry components. The mallee biomass collection area for the central bioenergy plant is assumed to be square, and the central bioenergy plant is located either at the center of the biomass collection area or distant from the center (Figure 1). Bio-oil and biochar can be produced in distributed pyrolysis plants, which include biomass drying, biomass pyrolysis, biochar grinding and bioslurry preparation, for green biomass processing. In this study, green biomass is defined as the whole-plant chipped mallee biomass that is produced from the harvester, in a flowable form of biomass particles with a length dimension of ~10 cm and a moisture content of 45%. The biochar will be ground into fine particles and then mixed with bio-oil to produce bioslurry fuels to facilitate road transport. Typically, the biomass will be dried prior to pyrolysis, and the pyrolytic gas and part of char products may be combusted to provide process heat.

Two scenarios are considered for comparing the costs of green biomass and bioslurry in terms of $A per GJ energy (LHV) delivered to the plant gate. As illustrated in Figure 1, scenario A is the delivery of bioslurry to a central processing plant located in the center of the biomass collection area. A typical example is a purposely-designed dedicated bioenergy plant. Scenario B is the delivery of bioslurry to a central processing plant which is distant from the center of the biomass collection area. Typical examples include the delivery of bioslurry fuels to a coal-fired power station or stationary engine in mines.

2.1. Biomass Production and Transport. The mallee biomass supply chain system includes biomass production, harvest, on-farm haulage, and road transport, which was developed in our previous study.[10] Details of the full mallee production system can be found elsewhere.[8] 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 mallee production system is assumed to have an average biomass productivity of 60 gt (green tonne) per hectare per harvest cycle, as indicated from the field data in WA. During each harvest, only the above-ground biomass of the mallee belts is harvested and chipped to produce biomass in a flowable form, while the root system is left in the ground for coppicing in the next harvest cycle. On-farm haulage transfers the biomass to a nearby roadside for road transport to deliver it to a central processing plant. The harvest and on-farm haulage are determined by harvester logistics depending on farm landscape attributes and infrastructure and biomass productivity.[44]

The average road transport distance of green biomass is determined by the plant capacity. This distance will be shorter for distributed pyrolysis plants producing bioslurry. The road transport cost is calculated by the biomass unit transport rate multiplied by the average road transport distance. The average biomass transport distance[45] (one-way) can be calculated by

$$r_b = \frac{1}{6}\tau\sqrt{\frac{P \times 330}{(1-\omega) \times 100 \times M \times l}}(\sqrt{2} + \ln(1+\sqrt{2})) \quad (1)$$

where τ is the tortuosity factor, and a constant value of 1.3 is used on the basis of our previous evaluation on the rural road system in the WA wheatbelt.[10] P is the processing capacity of the plant in dry tonnes per day, assuming that the plant operates 330 days per year. ω is the green mallee moisture content (%), 45% for green mallee biomass. l is land coverage of mallee planting (%), 2% used in this study considering biomass supply security, and M is mallee productivity, gt ha^{-1} year^{-1}, typically 20 gt ha^{-1} year^{-1} for a biomass productivity of 60 gt per hectare per 3-year harvest cycle. For the calculation of transport cost, the biomass unit transport rate of $A0.1−0.4 km^{-1} gt^{-1} is used for green biomass.

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Table 1. Biomass and Bio-Slurry Transport to a Central Processing Plant—Base Case and Sensitivity Analysis (Scenario A)

parameter	base case	sensitivity analysis
plant capacity (dry tonnes per day)	1000	100−3000
biomass unit transport rate ($\$$A km^{-1} gt^{-1})	0.2	0.1−0.4
number of distributed pyrolysers[a]	9	4−100
pyrolysis plant cost index[a]	1	0.5−1

[a] For bioslurry only.

2.2. Bioslurry Production and Transport. A pyrolysis system is considered for processing large green biomass particles to produce the biochar and bio-oil components of bioslurry. This system also considers biomass drying, the grinding of biochar and suspending the fine biochar particles into bio-oil for preparing bioslurry fuels. Hereafter, these distributed pyrolysis systems are also denoted as distributed pyrolysers. This study designed the pyrolysis system at a capacity of 100 dry tonnes of biomass per day and estimated the capital and operating costs. For pyrolysis systems at different processing capacities, the plant capital costs are estimated following the power law below:

$$C_s = C_0\left(\frac{P_s}{P_0}\right)^n \tag{2}$$

where C_0 is the capital cost for a plant with capacity P_0, and n is the scale factor, which is usually taken to be ~0.6. In this study, the main operating costs include labor, maintenance, insurance, and tax. The product yields, product properties, and required reaction heat of mallee biomass pyrolysis were reported previously,[28,31,32,46] and relevant data are considered in this study.

The average road transport distance of bioslurry from distributed pyrolysers to the central bioenergy plant is determined by the sizes of the central bioenergy plant and the distributed pyrolysers. It can be calculated by the following method:

$$r_s = \tau \times \bar{r} \tag{3}$$

where $\bar{r}$ is the average linear distance (one-way) from each pyrolyser to the central plant, and τ is same as that in equation (1). It should be noted that the average linear distance needs to be manually calculated for each pyrolyser. Similar to the method for calculating biomass transport cost, the transport cost of bioslurry is also determined by the unit transport rate multiplied by the average road transport distance. For the road transport of bioslurry, it is assumed that the transport is limited by the load volume of road trailers. At 20% biochar loading,[9] the bioslurry prepared from the biochar and bio-oil of fast pyrolysis of mallee wood at 500 °C contains ~21% moisture and has a volumetric energy density of bioslurry of ~23 GJ/m^3. Such a volumetric energy density is much higher than 5 GJ/m^3 of green biomass;[9] hence the unit transport rate (based on energy) of bioslurry will be cheaper.

For scenario B, the green biomass or bioslurry will be delivered to a plant located distantly from the center of biomass collection area, largely increasing the average road transport distance of green biomass or bioslurry. The average road distance of green biomass for scenario B was based on direct estimation. For the case of bioslurry, the average road transport distance for green biomass from the field to the pyrolysers is also calculated by equation 1, considering the capacity of distributed pyrolysers. As the central plant is not located in the center of the square biomass collection area, the average road transport distance depends mainly on the distance between the biomass collection area and the central processing plant.

Table 2. Breakdown of Delivered Costs for Green Biomass and Bioslurry for the Base Case (Scenario A)

cost	biomass delivered cost ($\$$A GJ^{-1})	biomass %	bioslurry delivered cost ($\$$A GJ^{-1})	bioslurry %
biomass production	1.28	21.3	1.37	23.8
biomass harvest	0.65	11.0	0.70	12.2
biomass on-farm haulage	1.36	22.9	1.46	25.4
biomass road transport	2.67	44.8	0.92	16.0
bioslurry road transport			0.34	6.0
plant capital and operating costs			0.96	16.6
total	**5.97**	**100.0**	**5.77**	**100.0**

3. Results and Discussion

3.1. Supply Chain for Central Processing Plant Located at the Centre of Biomass Collection Area. A base case is established for the supply chain of a central bioenergy plant situated at the center of the biomass collection area, as illustrated in Figure 1. For a biomass supply chain where biomass is directly used as the fuel, the biomass in the whole collection area is transported to the central plant. For a bioslurry-based supply chain, distributed pyrolysers are situated in the biomass collection area, and biomass is collected and transported to the distributed pyrolysers to produce bioslurry fuels. The bioslurry fuels from many distributed pyrolysers are then transported to the central bioenergy plant. A detailed analysis was then carried out for a base case to evaluate the delivered costs for green biomass and bioslurry to the gate of the central bioenergy plant. The base case considers a central plant capacity of 1000 dry tonnes of biomass per day and a biomass unit transport rate of $\$$A0.2 km^{-1} gt^{-1}. For a bioslurry-based supply chain, a total of nine distributed pyrolysers is considered, each with a processing capacity of ~111 dry tonnes of biomass per day. Based on these parameters (as summarized in Table 1), the delivered cost of a biomass-based supply chain for the base case is estimated to be $\$$A5.97 GJ^{-1} while that for bioslurry is $\$$A5.77 GJ^{-1}, as listed in Table 2. The results suggest that a bioslurry-based supply chain only leads to a slight reduction in the cost in term of per GJ delivered energy. Table 2 clearly shows that road transport dominates the delivered cost of green biomass, contributing ~45% of the delivered cost. When biomass is converted into bioslurry in the distributed pyrolysis plants, biomass road transport cost reduces by ~65%, from $\$$A2.67 to 0.92 GJ^{-1}. However, bioslurry production incurs additional costs associated with the introduction of distributed pyrolysers into the supply chain and bioslurry transport. Whether the bioslurry production is feasible depends on the trade-off between the reduction in biomass road transport cost and the increase in bioslurry road transport cost and capital and operating costs of these distributed pyrolysers.

Further sensitivity studies were conducted to evaluate the changes in delivered costs of biomass and bioslurry with key

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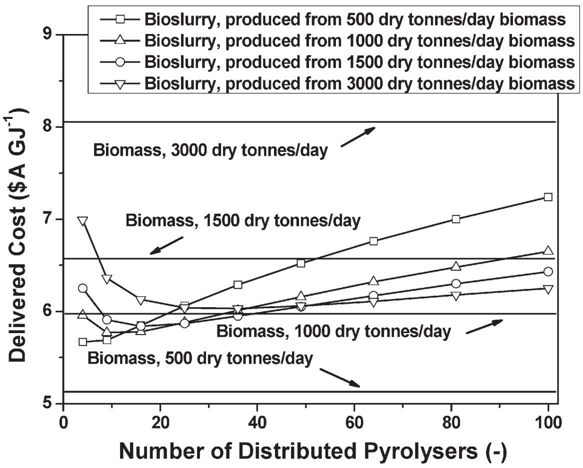

Figure 2. Delivered cost of bioslurry at the gate of a central plant of various capacities, as a function of the number of distributed pyrolysers (scenario A, \$A0.2 km^{-1} gt^{-1}).

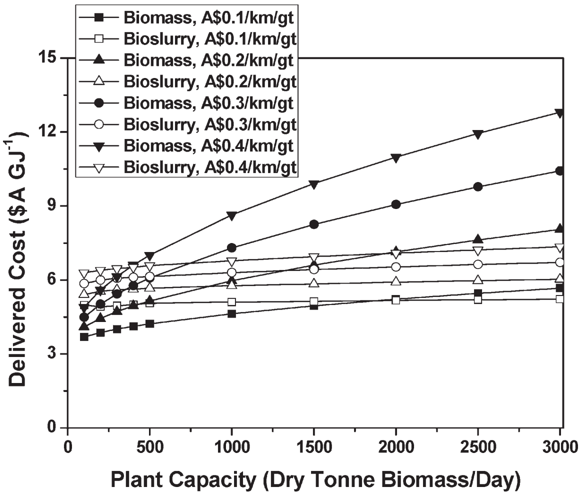

Figure 3. Delivered costs of biomass and bioslurry as a function of the central plant capacity at various biomass unit transport rates (scenario A, at optimal number of distributed pyrolysers). Note: Bioslurry is produced from the same amount of biomass.

parameters, particularly the number of distributed pyrolysers, biomass unit transport rate, and plant capacity. Figure 2 shows the delivered cost of bioslurry fuels at the gate of central bioenergy plant as a function of the number of distributed pyrolysers at various plant capacities. For a central plant with a capacity of 500 dry tonnes biomass (equivalent) per day, the delivered cost of bioslurry is always higher than that of green biomass, indicating that the saving in biomass road transport cost at 500 dry tonnes per day is not enough to compensate for the costs associated with the introduction of distributed pyrolysers for bioslurry production. For a capacity of 1000 dry tonnes biomass per day, the production of slurry becomes feasible when the number of pyrolysis plant is less than 36. Further increase in the number of pyrolysis plant will substantially increase the bioslurry cost due to the increase of plant capital and operating costs of distributed pyrolysers. A bioslurry-based supply chain is always cheaper than a biomass-based supply chain for large central plants of a processing capacity > 1500 dry tonnes per day. The results in Figure 2 clearly demonstrate that a bioslurry-based supply chain with distributed bioslurry

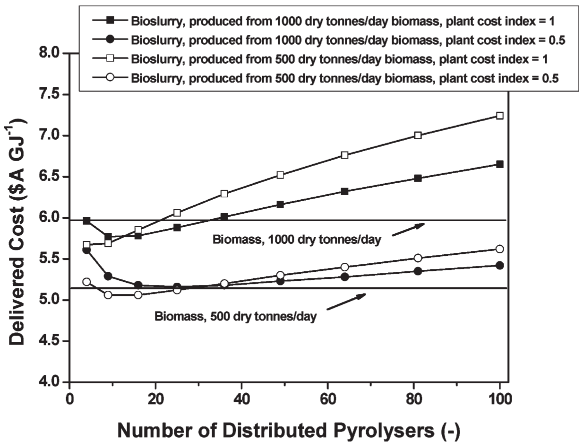

Figure 4. Effect of pyrolysis plant cost on the delivered cost of bioslurry (scenario A, \$A0.2 km^{-1}gt^{-1}).

production is not competitive for small bioenergy plants (e.g., < 500 dry tonnes per day), and green biomass is the better option for small bioenergy plants. Furthermore, for large-scale bioenergy plants, the number of distributed pyrolysers can be optimized to obtain the minimal delivered cost of bioslurry. As shown in Figure 2, the optimal number of distributed pyrolysers increases with central plant processing capacity, from 9 for 1000 dry tonnes per day, to 16 for 1500 dry tonnes per day, then to 36 for 3000 dry tonnes per day.

Figure 3 shows that delivered costs of biomass and bioslurry as a function of central plant capacity at various biomass unit transport rates. It should be noted that for each plant capacity in Figure 3, the number of distributed pyrolysers has been optimized to obtain the minimal delivered cost of bioslurry to the central plant gate. Figure 3 clearly shows that under optimized conditions, the delivered costs of biomass and bioslurry all increase with plant capacity. However, the delivered cost of bioslurry to the central plant gate is much less sensitive to the central plant capacity in comparison to that of biomass, mainly due to the substantially lower transport cost of bioslurry and the optimization of the number of pyrolysis plant. Again at small processing capacity of the central plant (e.g., < 400 dry tonnes per day), the delivered cost of biomass is always lower than that of bioslurry, even at the highest transport rate of \$A0.4 km^{-1} gt^{-1}. To make a bioslurry-based supply chain feasible, the central plant capacity has to be larger than a threshold capacity (i.e., the break-even value), which is largely determined by biomass unit transport rate. For example, at the biomass unit transport rate of \$A0.1 km^{-1}gt^{-1}, bioslurry production only becomes feasible when the central plant capacity is larger than ~2000 dry tonnes per day. This break-even value of the central plant capacity decreases when increasing the biomass unit transport rate. To make bioslurry production competitive at a small plant capacity of 500 dry tonnes per day, the biomass unit transport rate should be higher than \$A0.3 km^{-1}gt^{-1} for green biomass. The results in Figure 3 further demonstrate that a biomass-based supply chain is more suitable than a bioslurry-based supply chain for small bioenergy plants. A bioslurry-based supply chain is only feasible at a large bioenergy plant.

If future advances in pyrolysis technology can reduce the capital and operating costs for distributed pyrolysers, a bioslurry-based supply chain may become more competitive for smaller bioenergy plants. A sensitivity analysis was then

Table 3. Transport of Biomass and Bioslurry to a Large-Scale Coal-Fired Power Station (300 MWe Power Generation Capacity)—Base Case and Sensitivity Analysis (Scenario B)

parameter	base case	sensitivity analysis
bioenergy substitution[a] (%)	5	5−20
biomass unit transport rate ($A km^{-1} gt^{-1})	0.2	0.1−0.3
distance between plant and collection area (km)	100	25−200
number of distributed pyrolysers[b]	4	1−64

[a] 5% for biomass and 5−20% for bioslurry transport. [b] For bioslurry transport only.

carried out to evaluate the effect of distributed pyrolyser cost, as shown in Figure 4. It can be seen that at a 50% reduction in the capital and operating costs of distributed pyrolysers, the delivered cost of bioslurry will be reduced by ~$A0.7 GJ^{-1} at 500 dry tonnes per day, making a bioslurry-based supply chain feasible even at a biomass unit transport rate of $A0.2 km^{-1} gt^{-1}. At a higher central plant capacity (e.g., 1000 dry tonnes per day), there will be even more reduction in the delivered cost of bioslurry, compared to that of green biomass. It can also be seen that the optimal number of distributed pyrolysers increases with a reduction in the cost of pyrolysers. The results clearly show that, if the costs associated with the introduction of distributed pyrolysers into the supply chain can be reduced due to future technological advances, the distributed pyrolysers can be of very small scales. This is of particular importance if cheap small-scale (even mobile) pyrolysers become available and are used to further reduce biomass road transport distance and cost.

3.2. Supply Chain of Delivering Biomass/Bioslurry to Central Plants Distant from the Centre of Biomoass Collection Area. For scenario B in Figure 1, bioslurry fuels are transported away from the center of the biomass collection area. A dedicated bioenergy plant is obviously not economical if situated distant from the biomass collection area. Hence this scenario deals with the option where biomass and/or bioslurry is transported to large-scale coal-based plants for coprocessing. This study considers a 300 MWe coal-fired power station. It is known that direct biomass cofiring can only substitute up to 5% of coal (on an energy basis) in coal-fired power stations.[37−39] On the basis of an average efficiency of ~31% for a typical coal-fired power plant, the supply of biomass is estimated to be ~250 dry tonnes per day. Considering ~15% energy loss during bioslurry production and preparation, slightly more biomass will be required to substitute a 5% energy input of the power plant for bioslurry cofiring applications. The parameters of the base case analysis are listed in Table 3, which considers a transport distance of 100 km from the biomass collection area and the coal-fired power plant.

Table 4 shows the delivered costs of biomass and bioslurry, calculated using the parameters in Table 3. The delivered cost of green biomass for the base case is estimated to be $A9.44 GJ^{-1}, significantly higher than the $A6.30 GJ^{-1} of a bioslurry-based supply chain. Due to the increase in biomass road transport distance under scenario B, it constitutes ~65% of the delivered cost of biomass, compared to ~45% for scenario A. The majority reduction in delivered cost of bioslurry arises from the fall in biomass road transport cost, from $A6.14 to $A0.88 GJ^{-1}. This indicates that a bioslurry-based supply chain has considerable promise in situations where biomass has to be transported outside the collection area.

Table 4. Breakdown of Delivered Costs of Green Biomass and Bioslurry for the Base Case (Scenario B)

	biomass		bioslurry	
bioenergy cost	delivered cost ($A GJ^{-1})	%	delivered cost ($A GJ^{-1})	%
biomass production	1.28	13.6	1.76	21.7
biomass harvest	0.65	6.9	0.90	11.2
biomass on-farm haulage	1.36	14.4	1.88	23.3
biomass road transport	6.14	65.1	0.88	10.9
bioslurry road transport			1.11	13.7
plant capital and operating costs			1.56	19.2
total	**9.44**	**100.0**	**6.30**	**100.0**

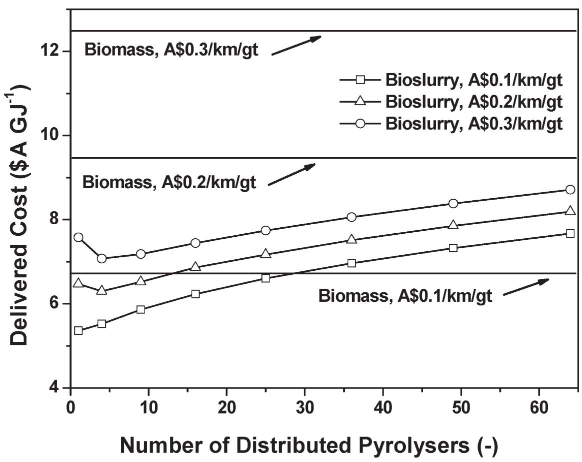

Figure 5. Delivered cost of bioslurry at various biomass unit transport rates, as a function of the number of distributed pyrolysers (scenario B, 5% energy substitution of a 300 MWe coal-fired power station, 100 km from the biomass collection area).

Figure 5 shows the delivered cost of bioslurry at biomass unit transport rates of $A0.1−0.3 km^{-1} gt^{-1}, as a function of the number of distributed pyrolysers. At a biomass unit transport rate of $A0.1 km^{-1} gt^{-1}, the delivered cost of bioslurry increases with the number of distributed pyrolysers. Further analysis shows that bioslurry road transport cost only increases slightly with an increasing number of distributed pyrolysers in the biomass collection area. As increasing numbers of distributed pyrolysers are deployed in the bioslurry supply chain, their capital and the operating costs of distributed pyrolysers increase. Their capacities also decrease, leading to a decrease in the green biomass transport cost within the collection area.The trade-off between these two aspects indicates that there might be an optimal number of pyrolysis plants required to achieve the minimal delivered cost for bioslurry. It can be seen in Figure 5 that at a biomass unit transport rate of $A0.2 and 0.3 km^{-1} gt^{-1}, the delivered cost of bioslurry reaches a minimum at an optimal four distributed pyrolysers. At a biomass unit transport rate of $A0.1 km^{-1} gt^{-1}, the reduction in biomass road transport cost is too small to offset the increase in the capital and operating costs of distributed pyrolysers, leading to no such optimum being reached. At high unit biomass transport rates (e.g., $A0.2 and 0.3 km^{-1} gt^{-1}), a bioslurry-based supply chain performs considerably better than a biomass-based supply chain. The number of distributed pyrolysers should be low and close to the optimal number (four in this case), since an increasing number of distributed pyrolysers leads to an increase in the delivered costs of bioslurry at the gate of a coal-fired power station. Figure 5 also shows that at a unit biomass transport rate of 0.1 A\$ km^{-1} gt^{-1}, the number of distributed pyrolysers should be less than 25 in order to ensure the competitiveness of a bioslurry-based supply chain when the distance between the coal-fired power station and the biomass collection area is 100 km.

Further evaluation has been conducted to investigate the effect of distance between coal-based plants and the biomass collection area on the delivered costs of biomass and bioslurry. As shown in Figure 6, both the delivered costs of biomass and bioslurry increase with distance, but the delivered cost of bioslurry is much less sensitive with distance. There is a minimal distance (break-even value) to make the bioslurry production feasible at different biomass unit transport rates, from 75 km at \$A0.1 km^{-1} gt^{-1}, to 40 km at \$A0.2 km^{-1} gt^{-1}, then to 25 km at \$A0.3 km^{-1} gt^{-1}. The savings between bioslurry and biomass will increase with the increase of distance and biomass unit transport rate. For example, for a biomass unit transport rate of \$A0.1 km^{-1} gt^{-1}, the delivered cost of bioslurry reduces by ~10% at 100 km, and ~34% at 200 km, compared to that of green biomass. Whereas for the biomass unit transport rate of \$A0.3 km^{-1} gt^{-1}, there will be ~41% reduction at 100 km, and ~59% reduction at 200 km.

3.3. Implications. The results in the previous sections illustrate that a bioslurry-based bioenergy supply chain can be

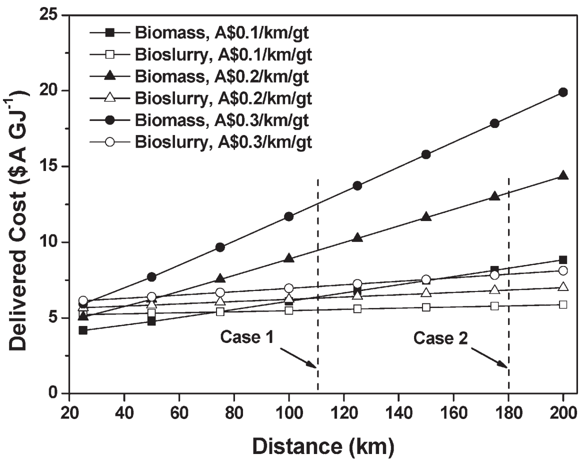

Figure 6. Delivered costs of biomass and bioslurry as a function of the distance at various biomass unit transport rates. Case 1: Biomass from Narrogin area to Muja power station. Case 2: Biomass from Katanning area to Muja power station (scenario B, 5% energy substitution of a 300 MWe coal-fired power station, 4 distributed pyrolysers).

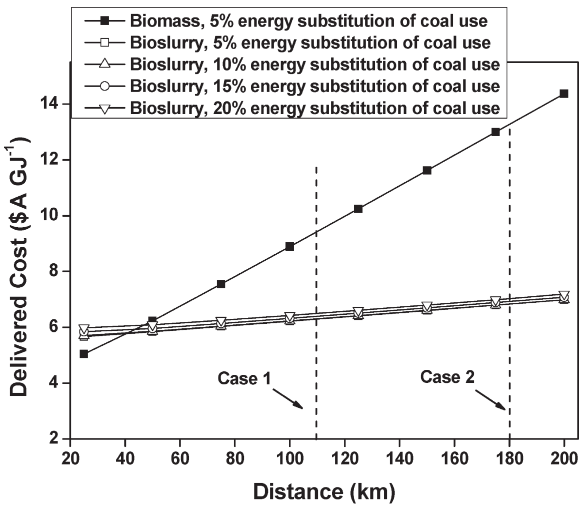

Figure 8. Delivered costs of bioslurry as a function of the distance at various energy replacements. Case 1: Biomass from Narrogin area to Muja power station. Case 2: Biomass from Katanning area to Muja power station (scenario B, 0.2 A\$ $km^{-1}gt^{-1}$, 4 distributed pyrolysers).

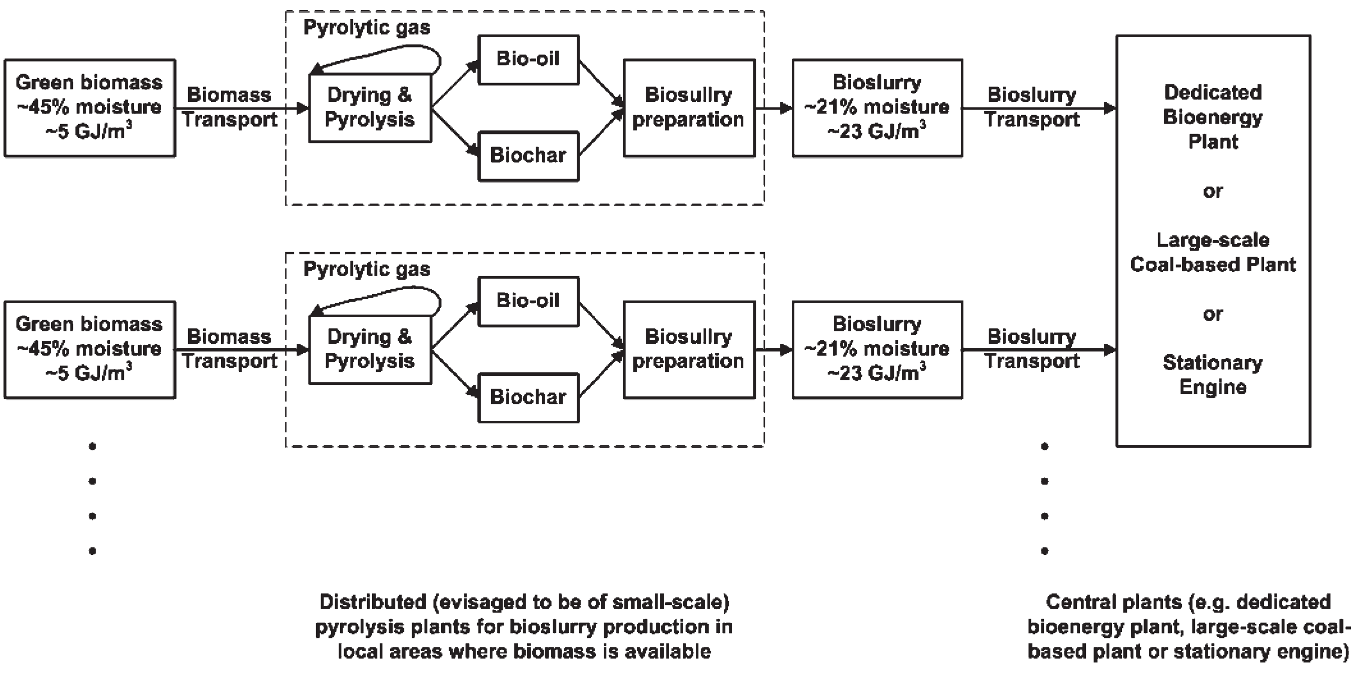

Figure 7. Bioslurry-based bioenergy supply chain based on a combination of a number of distributed pyrolysers near biomass production area and a central processing plant.

viable and attractive, particularly in scenario B, where a number of distributed pyrolysers are deployed within the biomass production area to produce bioslurry that is subsequently delivered to a distant central processing plant. As illustrated in Figure 7, the supply chain can potentially offer significant advantages to a biomass-based supply chain:

- Via pyrolysis, green mallee (size, ~10 cm; mositure content, 45%; volumetric energy density, 5 GJ/m^3) can be converted to bioslurry fuels (moisture, 21%; volumetric energy, ~23 GJ/m^3 at 20% char loading).[9] Instead of green biomass, bioslurry is transported, and this successfully addresses the issue of high transport costs associated with biomass transport.
- It takes advantages of the excellent grindability of biochar.[16,17] Converting large biomass particles into biochar, grinding the biochar, and then suspending the fine char particles into bio-oil for producing the bioslurry addresses the key issues associated with the poor grindability of biomass.
- Through energy densification via pyrolysis, bioslurry fuels have fuel properties much closer to coal.[9] Bioslurry conversion produces much less flue gas in the boiler and addresses the key issue of mismatch in fuel properties between biomass and coal during coprocessing (e.g., cofiring in coal-fired boilers or cogasification in coal gasifiers).
- The distributed pyrolysers take large biomass particles as feed and are adaptive to deal with any biomass as the feed. Bioslurry fuels can also be easily adapted to the existing vast coal-based power generation infrastructure.

A bioslurry-based bioenergy chain may have significant implications on the mallee biomass industry in WA. Biomass cofiring has been tested in the Muja power station, which is one of the two coal-fired power stations in the state. Muja power station is located on the Collie coal field and burns sub-bituminous coal from adjacent mines. Mallee biomass can potentially be produced in the wheatbelt area > 100 km to the east. Two potential mallee production areas have been nominated, centered on the towns of Narrogin and Katanning, which have distances of ~110 km and ~180 km to the Muja power station, respectively. As shown in Figure 8, a bioslurry-based supply chain for cofiring applications in the Muja power station can lead to a substantial reduction in cost. Additionally, bioslurry has the potential to be cofired with coal at a higher energy substitution ratio, compared to 5% for cofiring biomass and coal. An analysis was also then conducted to compare the delivered cost of bioslurry when bioslurry is used to substitute coal at various energy substitution ratios (5−20%). For the case of the Narrogin to Muja power station, Figure 8 clearly shows that the delivered cost of bioslurry is insensitive to the bioenergy substitution ratio in a coal-fired power plant from 5 to 20%. The results suggest that bioslurry as a fuel for cofiring in a coal-fired power plant has the significant potential to increase bioslurry uptake and is economically more competitive than green biomass.

4. Conclusions

This study shows that a bioslurry-based bioenergy supply chain can only be economically competitive when the increase in costs associated with the introduction of distributed pyrolysers into the supply chain and bioslurry transport can be offset by a reduction in biomass transport cost. For dedicated bioenergy plants situated inside WA's wheatbelt area where mallee biomass can be grown, small dedicated bioenergy plants (e.g., < 500 dry tonne per day) would still favor a biomass supply chain. A bioslurry-based supply chain is only feasible on much larger scales (e.g., 1500 dry tonne per day). However, for the cofiring option of mallee biomass in existing coal-fired power stations in WA, a bioslurry-based bioenergy supply chain can substantially reduce the delivered cost of fuels. It can also significantly increase bioenergy uptake (e.g., to 20% on an energy basis) for substituting coal use in coal-fired power stations, from merely 5% in a biomass supply chain.

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