BIOENERGY
AUSTRALIA

BIOENERGY IN AUSTRALIA
Status and Opportunities

by Colin Stucley, Stephen Schuck, Ralph Sims, Jim Bland, Belinda Marino, Michael Borowitzka, Amir Abadi, John Bartle, Richard Giles, Quenten Thomas

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Foreword

Bioenergy - for heat, power and liquid fuels – is the subject of considerable interest and activity world-wide. Drivers for bioenergy include:

- the reduction of CO_2 emissions via the substitution of bioenergy for fossil fuels.
- security of energy supplies.
- regional development and employment, especially through new rural industries.

With revenues in excess of $400 million per year, Australia's bioenergy industry is already a valued contributor to businesses in cities and rural locations across the country. Bioenergy has the potential for a much greater role in the future:

- Biofuels feature as a source of both electricity and liquid fuels in carbon reduction scenarios modelled in 2008 by the CSIRO[7].
- Referring to electricity production to 2020 and beyond, the Clean Energy Council of Australia states: "*Bioenergy has a vital role to play as part of Australia's clean energy future*"[8].
- After studying the role for biofuels as a future transport fuel in Australia, the Australian Academy of Technological Sciences and Engineering (ATSE) stated: "*The key finding of this report ... is that biofuels…have useful roles to play as Australian transport fuels and can contribute to greenhouse gas mitigation and energy security*."[9]
- Overseas, the US Government's Roadmap for Bioenergy and Biobased Products[10] states: "*Biomass resources are a sustainable and environmentally friendly feedstock that can contribute significantly to a diverse energy portfolio*."
- The European Union's position is similar: "*In the face of Europe's increasing dependency on fossil fuels, using biomass is one of the key ways of ensuring the security of supply and sustainable energy in Europe*."[11]

Bioenergy is a complex topic:

- It encompasses multiple feedstocks from agriculture, forestry, and urban sources. Energy products include electricity, heat and liquid fuels. In the future it is possible that co-products will also feature in many bioenergy projects.
- It includes many different technologies and feedstocks: some widely used for decades, others only recently or yet to be commercialised.

This report commissioned by Bioenergy Australia is a general resource for anyone interested in bioenergy: its feedstocks, its many different facets and its potential. It supplements the publicly available information on bioenergy available from the Bioenergy Australia web page www.bioenergyaustralia.org.

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[8] Australian Bioenergy Roadmap - http://www.cleanenergycouncil.org.au/bioenergy/

[9] Biofuels for Transport: A Roadmap for Development in Australia., by ATSE, November 2008

[10] Executive Summary of Roadmap for Bioenergy and Biobased Products in the United States, by Biomass Research and Development Technical Advisory Committee, October 2007

[11] http://europa.eu/legislation_summaries/energy/renewable_energy/l27014_en.htm

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The purpose of this report is to provide an overview of some of the options for renewable energy via biomass. While care has been taken in the preparation of the information in this document, the work undertaken is preliminary in nature and the authors and BAFL accept no responsibility or liability for any loss or damage that may be incurred by any person acting in reliance on this information.

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1. Energy use in Australia

1.1 Summary

Australia has extensive energy resources and is currently the largest exporter of coal in the world. Australia's total energy consumption in 2007-2008 was 5,772 PJ, while overall production was far greater, at 17,360 PJ.

Bioenergy currently provides approximately 4 % of Australia's Total Primary Energy Supplies (TPES) and makes up 78 % of the reported renewable energy. The latter percentage is in part due to the use of some four to six million tonnes of firewood per year. Other large energy contributions are from bagasse (sugar cane residues) and wood waste in heating and electricity generation, as well as capture and use of methane gas from landfill and sewage facilities. In recent years ethanol and biodiesel have also provided significant inputs.

The use of bioenergy for electricity generation in Australia has expanded considerably over the past decade or so. This expansion has been supported by Australian Government renewable energy schemes, initially the Mandatory Renewable Energy Target (MRET) and now the Large-scale Renewable Energy Target (LRET). Bioenergy currently provides approximately one percent of Australia's electricity.

Bioenergy also contributes to Australia's current needs for transport fuels. Ethanol and biodiesel are manufactured locally from materials such as molasses, waste starch, tallow and used cooking oil. In total they provide approximately two percent of Australia's current transport fuels.

It is predicted that Australia's overall energy consumption will continue to grow slowly over coming decades, with one major review suggesting average growth of 1.4 %/year to reach consumption of 7,715 PJ/year by 2029-2030. Bioenergy production is expected to grow at a faster rate and progressively provide a greater proportion of Australia's electricity and transport fuel needs. Work by ABARE, CSIRO, the Clean Energy Council, and the Australian Business Roundtable on Climate Change describes the potential for increased production of bioenergy. These reports suggest that, in the longer term, bioenergy could provide 20% or more of Australia's electricity or transport fuels. Such increased bioenergy use can be supported in particular by:

- The development of large resources of sustainable biomass around Australia that are not currently being used for bioenergy. Particular opportunities involve existing agricultural residues, and future tree planting on farms for biomass and other environmental benefits (such as belts of mallee trees).
- The commercial development of multiple technologies for conversion of biomass into biofuels.

1.2 National energy endowment and consumption

Australia is richly endowed with energy resources. It holds 38 percent of the planet's uranium resources, nine percent of coal resources and two percent of natural gas resources[1]. It produces approximately 2.4 percent of the world's energy and exports more than three-quarters of this to other countries. Australia is currently the world's largest exporter of coal.

Australia's energy *production* was 17,360 PJ in 2007-2008, with coal accounting for 54 percent of this production. In that year, total primary energy *consumption* was 5,772 PJ, with renewable energy accounting for 5 percent of the primary energy consumption.

Total electricity production was approximately 925 PJ (257 TWh) in 2007–08. Coal accounts for approximately three-quarters of Australia's electricity generation, followed by gas at 16 percent. Renewable energy sources account for an estimated 7 percent of national electricity generation, most

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[1] Geoscience Australia and ABARE, 2010, Australian Energy Resource Assessment (AERA), Canberra.

of which is hydroelectricity in Tasmania and from the Snowy Mountains hydroelectricity scheme and having a combined capacity of 7.8 GW.

Wind energy has been growing rapidly in Australia, with an installed capacity of approximately 2 GW, which provided approximately 1.5 percent of Australia's electricity in 2007-2008.

Solar photovoltaics and solar hot water systems have also grown rapidly over recent years, being the subject of both state and federal government support. This is discussed under the Renewable Energy Target section below.

Wind and solar energy accounted for only 0.3 percent of primary energy consumption in 2007-2008.

While not yet used commercially, ocean and geothermal energy are under active development in Australia. Hot rock geothermal energy is surmised to be able to provide substantial base load electricity in the future, although the technology is still to be operated at a commercial scale.

Bioenergy is a uniquely flexible source of renewable energy, contributing to the power, thermal energy and liquid fuel markets. Bioenergy currently provides approximately 4 percent of Australia's Total Primary Energy Supplies (TPES) with bioenergy providing 78 percent of the reported renewable energy. This high percentage is in part due to the use of some four to six million tonnes of firewood per year. Other large energy contributions are from bagasse (sugar cane residue) and wood waste in heating and electricity generation, as well as capture and use of methane gas from landfill and sewage facilities.

Table 1-1 summarises Australia's non-nuclear energy resources.

Table 1-1 Australia's energy resources, December 2008

Resource	Total Demonstrated Resources (PJ)	Production 2007-2008 (PJ)	Installed Electricity generation capacity (GW)	Electricity production 2007-2008 (TWh)
Black coal	1,046,500	8,722	24	143
Brown coal	896,300	709	6.7	60
Conventional gas	180,400	1,709	14	42 (includes CSG)
Coal seam gas (CSG)	46,590	124	Included in conventional gas	Included in conventional gas
Condensate (transport fuel)	16,170	257	-	-
Crude oil	8,414	697	1 (distillate)	-
LPG	6,210	105	-	-
Geothermal	>2,500,000	0.003	0.0001	0.0007
Hydro	100 TWh/a (tech exploitable)	43	7.8	12
Wind	>600,000 km² with average wind speeds >7m/s.	14	1.7	3.9
Solar	Average insolation 58 million PJ	7	0.1	0.1
Ocean	3.47	-	0.0008	-
Bioenergy all forms	See Table 1-6	226	0.9	2.2

Source: Geoscience Australia and ABARE, AERA

Figure 1-1 summarises Australia's total consumption of bioenergy over the past five decades. This includes small amounts of transport fuel (ethanol and biodiesel).

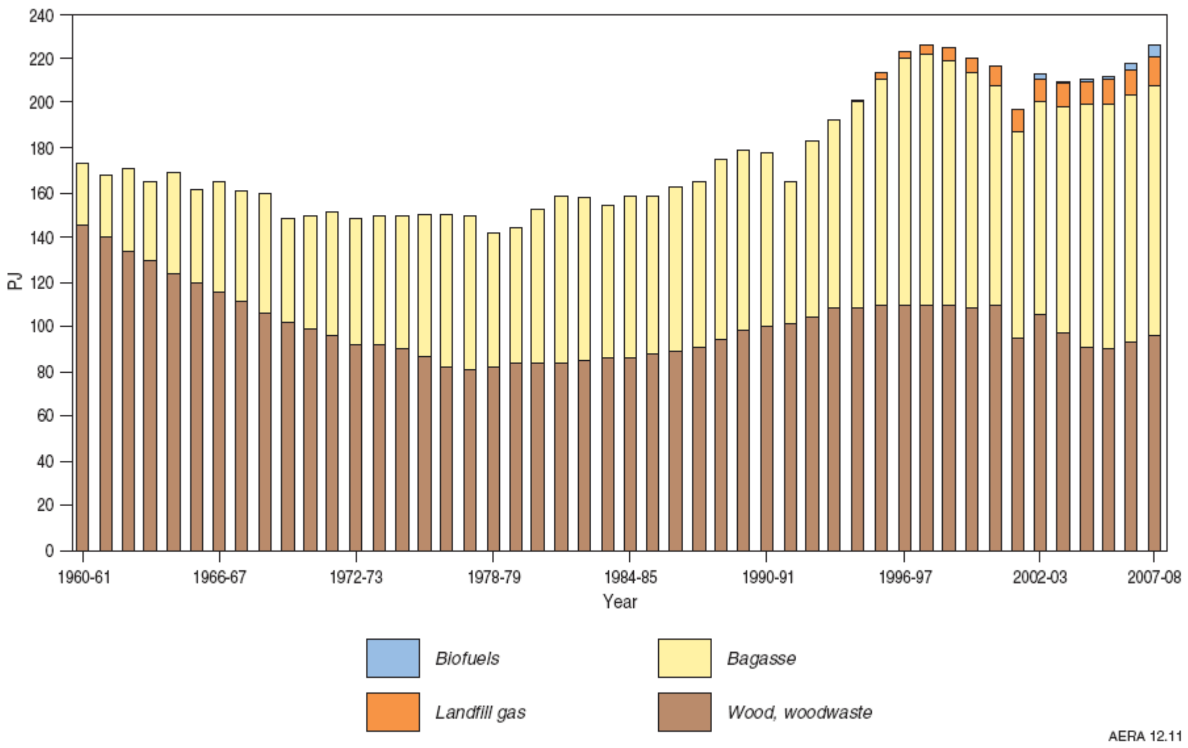

Figure 1-1 **Australia's primary consumption of bioenergy**[2]

1.3 Electricity

The stationary power sector comprises the large scale power, thermal energy and cogeneration subsectors. Across the whole of Australia, coal provides over three-quarters of Australia's electricity, followed by gas (natural gas and coal seam gas). This is illustrated in Figure 1-2.

The National Electricity Market (NEM) includes the eastern states of Tasmania, SA, Vic, NSW and Qld). Across the NEM, coal provided 82.3 percent of all electricity in 2009, gas 8.4 percent, and large-scale renewables 9.3 percent. Relative to the NEM, Western Australia uses a higher proportion of gas and less coal. Renewables for stationary power included 66 percent from hydroelectricity, wind energy 21 percent, and bioenergy 13 percent[3], with negligible or zero large scale solar energy, ocean energy or geothermal.

Electricity via bioenergy (bioelectricity) generated 2.5 million MWh (9 PJ) in 2009 in the NEM. Queensland has the largest bioenergy sector of any state, accounting for nearly half of this total. It has more than 40 bioenergy plants, with the biggest generator at the Pioneer sugar mill producing 0.24 million MWh in 2009.

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[2] Geoscience Australia and ABARE, 2010, Australian Energy Resource Assessment (AERA), Canberra

3 The Electricity Generation Report 2009, www.theclimategroup.org/_assets/files/Greenhouse-Indicator-Generation-Report-2009.pdf cited at the Bioenergy Australia 2010 conference by Brazzale.

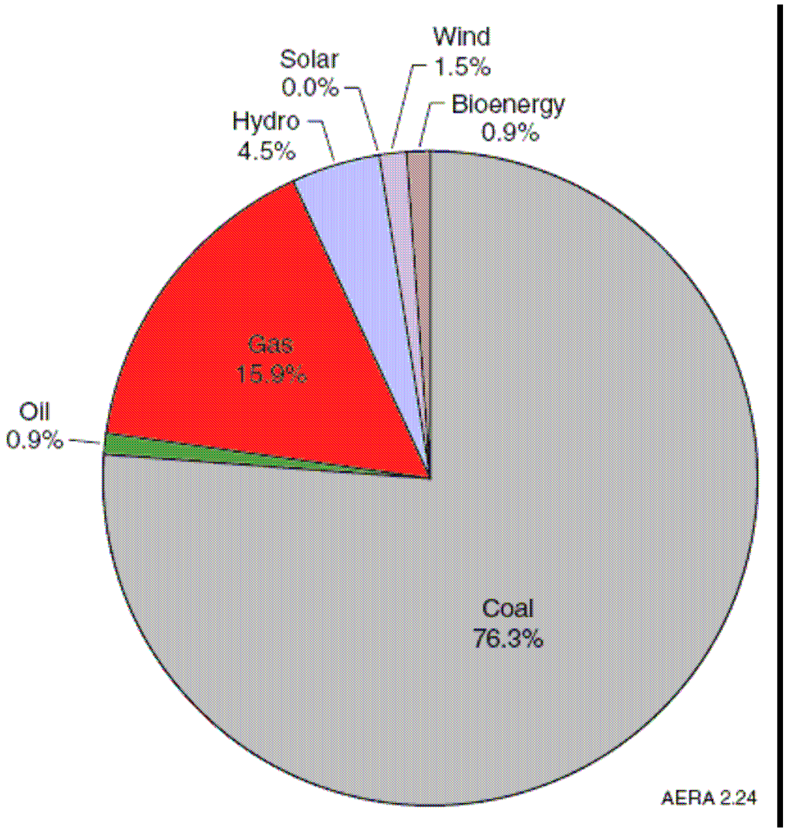

Figure 1-2 Electricity generation by fuel, 2007-08[4]

Figure 1-3 shows the contributions to renewable energy generation in the NEM in both 2008 and 2009.

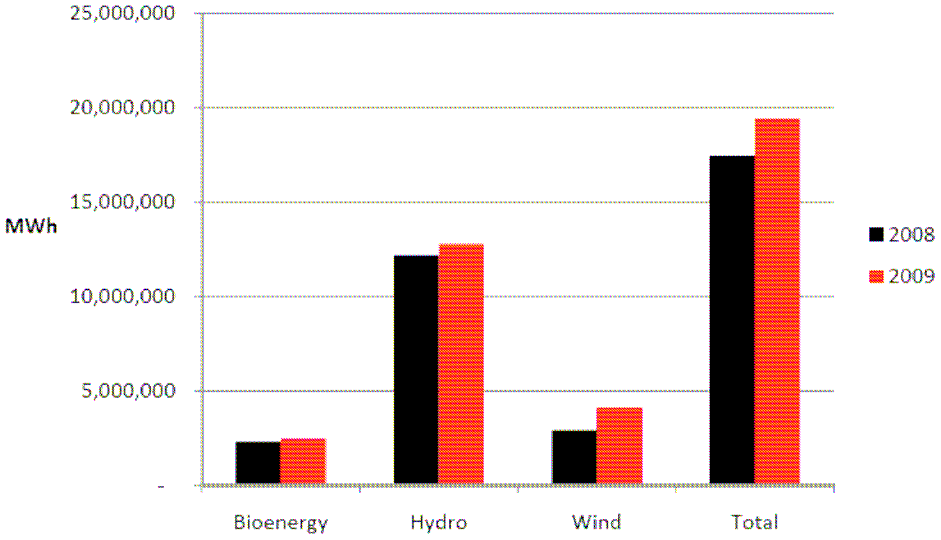

Figure 1-3 Renewable energy generation by sector 2008 and 2009[5]

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[4] Geoscience Australia and ABARE, 2010, Australian Energy Resource Assessment, Canberra.

[5] The Electricity Generation Report 2009, www.theclimategroup.org/_assets/files/Greenhouse-Indicator-Generation-Report-2009.pdf page 4.

Figure 1-4 shows total Australian electricity generation from bioenergy over recent years, with this electricity currently providing approximately 0.9 percent of total electricity generation.

From 1989-90 to 2007-08, annual bioenergy electricity generation grew at an average rate of 6 percent per year, reaching a total of 2.2 TWh (7.9 PJ) in 2007-08. The share of bioenergy in total electricity generation increased from 0.5 percent to 0.9 percent over that period.

Table 1-2 shows the contributions to electricity from bioenergy by state and major fuel type. Bagasse-fuelled electricity generation facilities represent 54 percent of total bioenergy capacity, at 464 MW.

Table 1-3 provides a listing of several bioenergy plants that are represented in Figure 1-4.

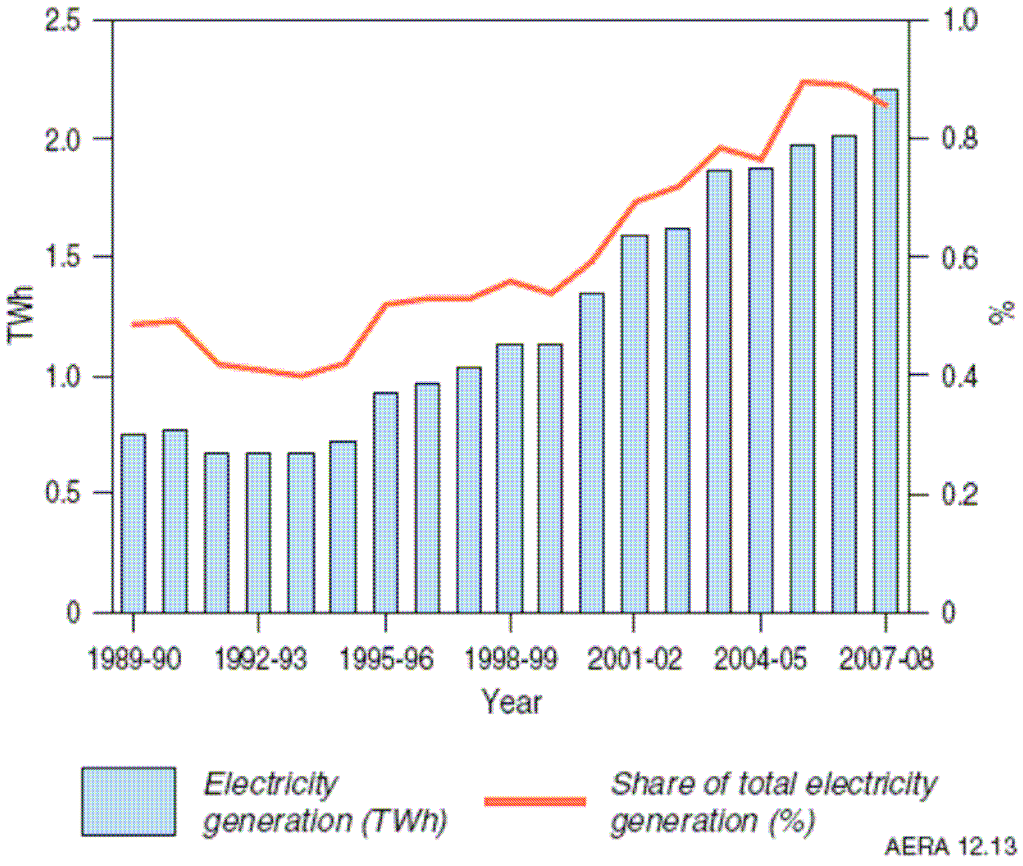

Figure 1-4 Australian electricity generation from bioenergy

Table 1-2 Australian electricity generation from bioenergy (MW), 2009[6]

	Biogas	Bagasse	Wood Waste	Other bioenergy [b]	Total bioenergy
New South Wales [a]	73	81	42	3	199
Victoria	80	0	0	34	114
Queensland	19	377	15	4	415
South Australia	22	0	10	0	32
Western Australia	27	6	6	63	102
Tasmania	4	0	0	0	4
Northern Territory	1	0	0	0	1
Australia	226	464	73	104	867
Share of total renewable electricity capacity (%)	2.2	4.4	0.7	1.0	8.3

a Includes the ACT *b Unspecified biomass and biodiesel*
Source: Geoscience Australia and ABARE, 2010

Table 1-3 Examples of Australian bioenergy plants commissioned over the past decade

Project	Company	State	Type	Start Up	Cap (MW)
Tumut	Visy Paper	NSW	Wood waste	2001	17.0
Rocky Point	National Power, and Babcock and Brown Joint Vent.	QLD	Bagasse	2001	30.0
South Cardup	Landfill Management Services Ltd	WA	Landfill methane	2005	3.3
Werribee (AGL)	AGL	VIC	Sewage methane	2005	7.8
Pioneer 2	CSR Sugar Mills	QLD	Bagasse	2005	63.0
Woodlawn	Woodlawn Bioreactor Energy Pty Ltd	NSW	Landfill methane	2006	25.6
Carrum Downs 1 & 2	Melbourne Water	VIC	Sewage methane	2007	17.0
Eastern Creek 2	LMS Generation Pty Ltd	NSW	Landfill methane	2008	8.8
Condong	Sunshine Electricity	NSW	Bagasse	2008	30.0
Broadwater	Sunshine Electricity	NSW	Bagasse	2008	30.0

Source: Geoscience Australia and ABARE 2010

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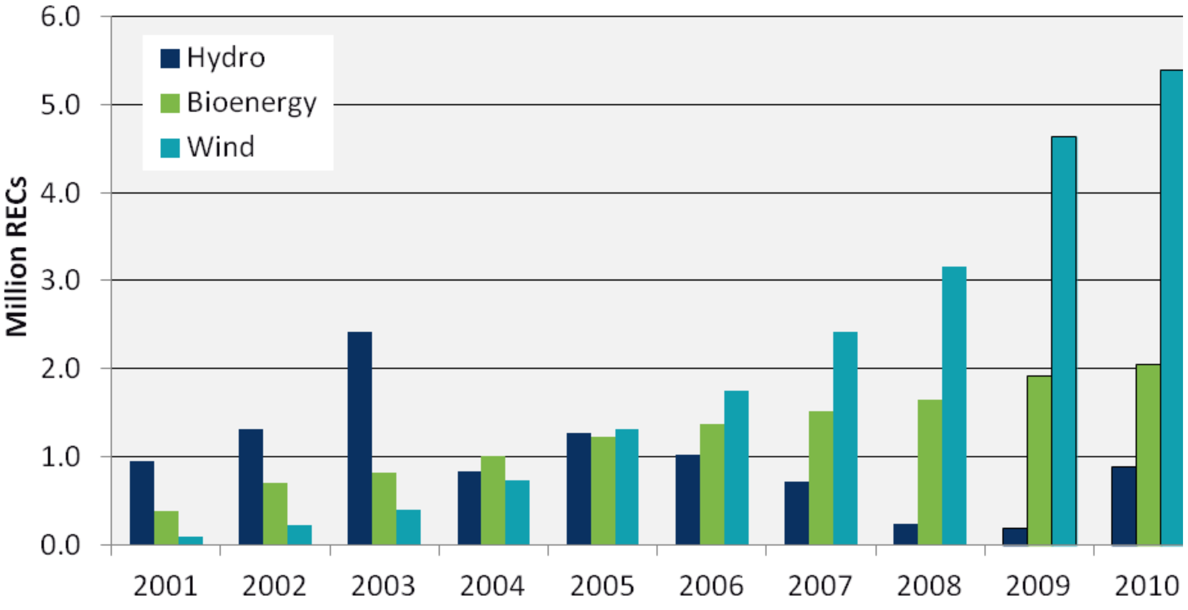
[6] Geoscience Australia and ABARE, 2010, Australian Energy Resource Assessment, Canberra

1.3.1 Renewable energy target

The Australian Government has set a national target for 20 percent of Australia's electricity to be sourced from renewable energy sources by 2020. The primary mechanism for achieving this target is via the Renewable Energy Target, which will require an additional 45,000 GWh (162 PJ) per year by 2020, with the RET applying until 2030. The RET operates through the creation and surrender of Renewable Energy Certificates, each certificate being for 1 MWh of compliant renewable energy. The RET requires liable entities (energy retailers and large energy users) to purchase a proportion of their energy requirements from renewable energy sources. The penalty for non-compliance has been set at $65 per MWh of shortfall. The RET is administered by the Federal Government's Office of the Clean Energy Regulator[7]. Figure 1-5 provides a breakdown of the contributions to the RET from wind energy, hydroelectricity and bioenergy over the period 2001 to 2010.



Source: Brazzale BEA 10 Green Energy Markets

Figure 1-5 **REC creation by energy source**

Figure 1-6 below provides a breakdown of the various forms of bioenergy that have contributed to the overall total show above.

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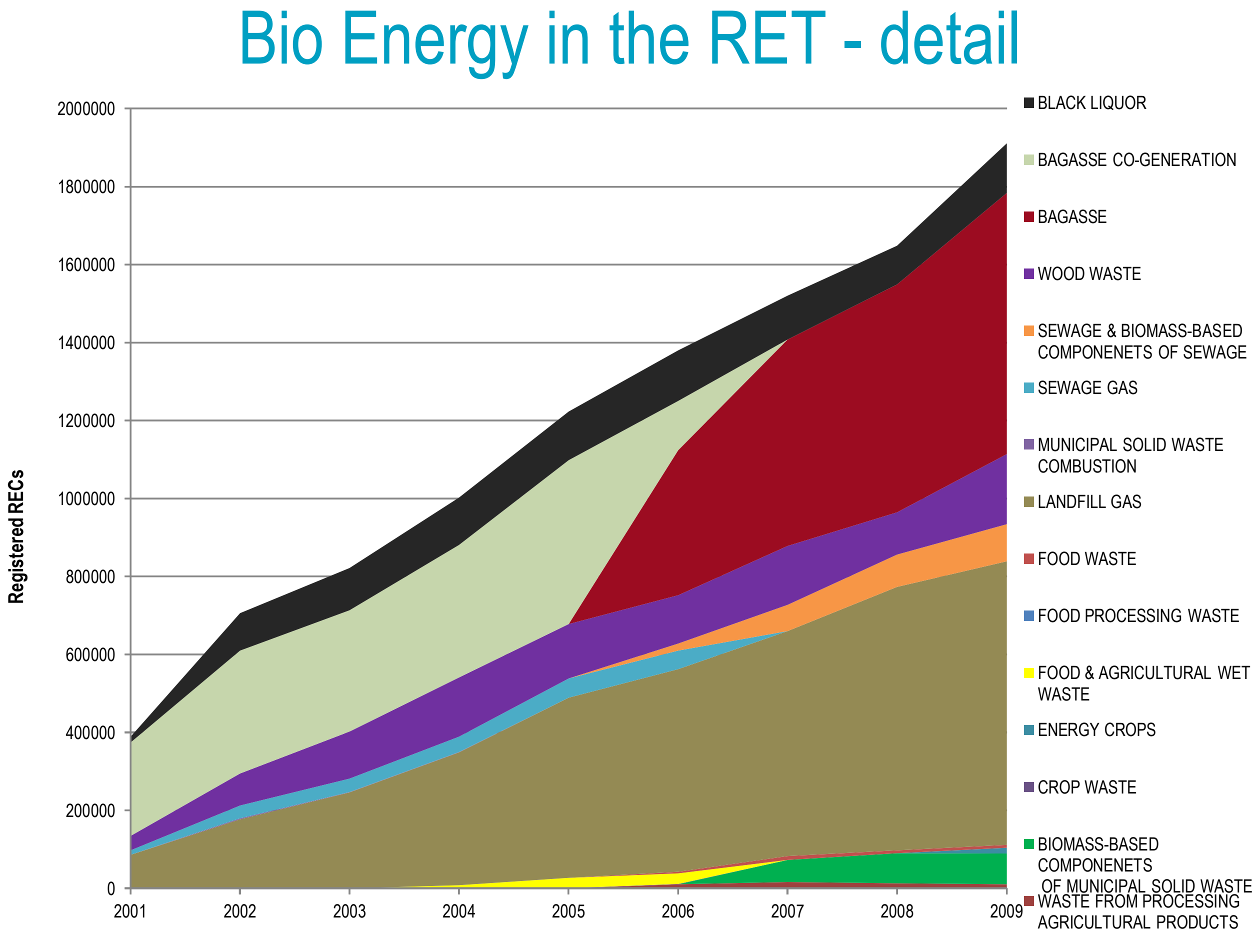
[7] Brazzale BEA 10 Green Energy Markets



(Source: ORER)

Figure 1-6 REC distribution by bioenergy type

1.3.2 Bioenergy under the LRET

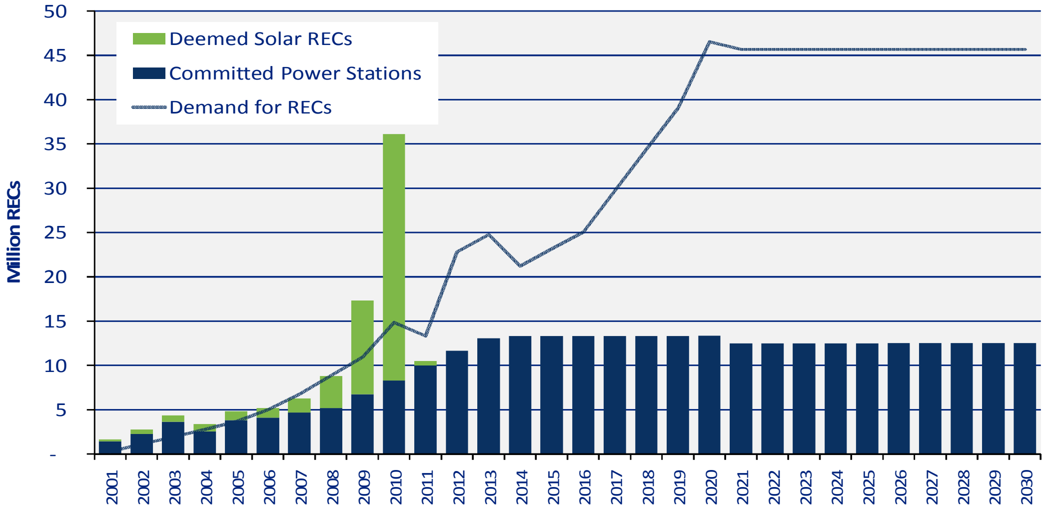
As of 1 January 2011 the Renewable Energy Target has been divided into two parts: the Large-scale Renewable Energy Target (LRET) and Small-scale Renewable Energy Scheme (SRES). The SRES focuses on domestic solar photovoltaic systems, solar water heaters and heat pump systems.

The LRET target is 41,000 GWh while the SRES is uncapped. The Federal Government has estimated that the SRES will deliver 11,000 GWh by 2020.

The Large-scale Renewable Energy Target operates via the creation and surrender of renewable energy certificates (RECs) known as Large-scale Generation Certificates (LGCs). Besides the mandatory market a smaller, voluntary market exists for GreenPower where qualifying RECs are surrendered to evidence the generation of GreenPower compliant renewable energy (which for GreenPower excludes bioenergy from native forestry biomass and via co-firing of biomass with coal).

Closely linked to GreenPower are certificates voluntarily surrendered against renewable energy for desalination plants and other water infrastructure projects. This currently totals approximately 1,700 GWh/a. GreenPower sales are expected to stabilise at 4.5 million MWh per year by 2020.

Figure 1-7 illustrates the overall market pull for large-scale renewable energy to 2030 from the LRET, including GreenPower sales. The figure also shows committed power stations.



Source: Green Energy Markets

Figure 1-7 Total demand for RECs including GreenPower sales

While the above shows a large surplus in the supply of RECs in 2009 and 2010 due to deemed solar RECs, this analysis by Green Energy Markets indicates that diverting solar RECs into the SRES, and the growth of the overall RET target to 2020 provide a very significant market for new renewable energy power plants (the area between the Demand for RECs curve and the committed power stations trajectory).

1.4 Liquid fuels

Australia's resources of oil (including condensate and LPG) are more limited than coal, and the country is becoming increasingly reliant on imported liquid fuels to meet its domestic consumption, as illustrated in Figure 1-8.

The installed annual capacity for biofuels in Australia in 2012 is reported by the Biofuels Association of Australia as follows:

- Ethanol capacity is 440 ML/year nationally, from two plants in Queensland and one in NSW [8].
- Installed biodiesel capacity at the start of 2012 was 200 ML/year, based on seven plants around the country[9]. These plants are designed to process a variety of feeds, with the plants currently in production processing mainly tallow and used cooking oil. Another plant, designed to produce 288 ML/year from a feed of soybeans, was announced in 2009[10] and groundbreaking for construction of the plant occurred in April 2012[11].

So the installed capacity for ethanol and biodiesel in Australia at the start of 2012 represents slightly less than 2% of the transport fuel consumed nationally.

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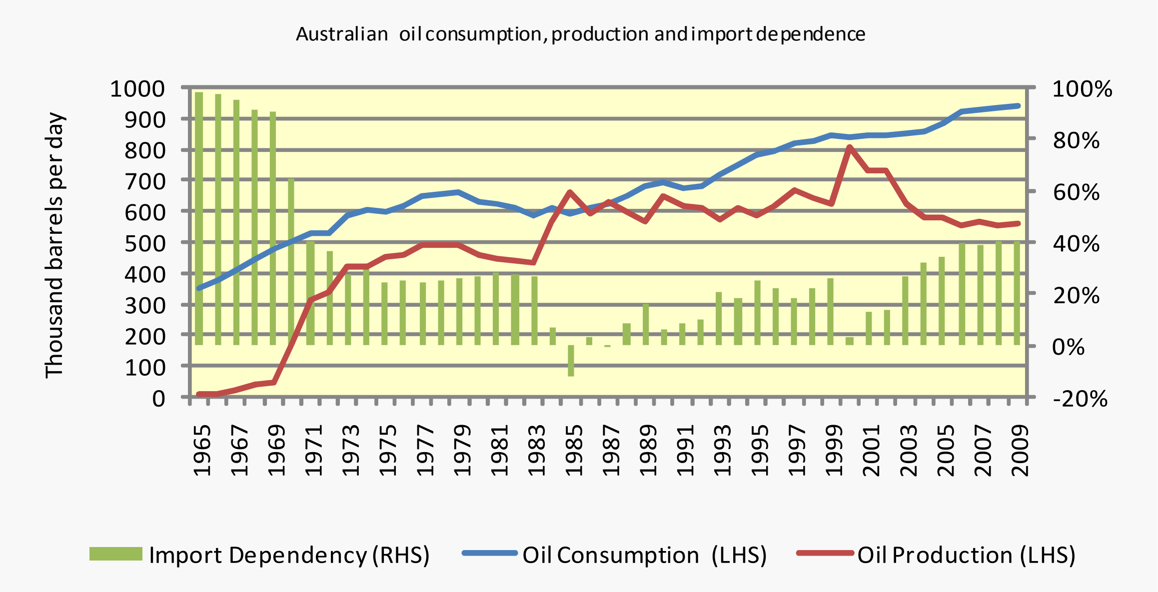
[8] http://www.biofuelsassociation.com.au/images/stories/pdf/ethanolmap.pdf
[9] http://www.biofuelsassociation.com.au/images/stories/pdf/biodieselmap.pdf
[10] http://www.abc.net.au/news/2009-05-19/port-kembla-to-get-biodiesel-facility/1686986
[11] http://www.natbiogroup.com/default.asp?id=77



Source: BP/APAC Biofuel Consultants – BEA 10 Cochrane

Figure 1-8 **Australian oil consumption, production and import dependence**

Table 1-4 **The annual consumption of petrol and diesel and turbine (jet) fuel for transport in Australia**[12]

Transport fuel	Year 2009/10 (ML)	Year 2005/06 (ML)	Change over five years
Petrol	18,644	19,048	Down, by 2%
Diesel	19,044	15,804	Up, by 21%
Turbine fuel	6,675	5,359	Up, by 25%
Total	44,363	40,211	Up, by 10%

1.5 Bioenergy for thermal applications

The heat component of industrial cogeneration (such as alongside sugar mills) and dedicated industrial thermal energy are not supported by a specific mandatory target or RECs in Australia. Nevertheless a range of thermal energy projects have proceeded, generally using process wastes such as sawdust at sawmills. Table 1-5 tabulates several such thermal applications using biomass.

Besides industrial heat applications using biomass, Australia uses some 4 to 6 million tonnes of firewood for space and water heating. An Australian company, Plantation Energy Australia has exported wood pellets from Western Australia, mainly to Europe for electricity generation. There has been some minor development of wood pellets for domestic heating in Australia using specially designed pellet heaters and boilers. The redevelopment of the Royal Children's Hospital in Melbourne incorporates a pellet boiler as part of its energy system.

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[12] http://www.ret.gov.au/energy/Documents/facts-stats-pubs/Energy-in-Australia-2011.pdf

Table 1-5 Examples of bioenergy thermal plants

Client	Plant Location	Capacity MW(thermal)	Product	Fuel
Visy Pulp & Paper	Melbourne, Vic	30	Water tube boiler	Sludge & Wood waste
ITC	Launceston, TAS	3	Water tube boiler	Dry Chip / Shavings
Nestlé	Gympie, QLD	16	Water tube boiler	Coffee waste / Wood waste
FEA	Georgetown TAS	20	Water tube boiler	Wood waste
Hyne & Son	Tumbarumba, NSW	15	Thermal Oil Heater	Wood waste
Carter Holt Harvey	Oberon, NSW	12	Thermal Oil Heater/Fibre drying	Wood waste (MDF waste and sawmill waste)
AKD Sawmill	Colac, VIC	15	Thermal Oil Heater	Wood waste
Hyne & Son	Tuan, QLD	12.5	Thermal Oil Heater	Wood waste
Starwood Australia	TAS	22	Water tube boiler	Biomass
Laminex	Gympie, Qld	24	Thermal Oil Heater	Wood waste
Carter Holt Harvey	Gympie, Qld	10	Hot gas – dryer	Dust, fuel oil
Carter Holt Harvey	Tumut, NSW	20	Hot gas – tunnel dryer	Wood waste, dust

Source: RCR Energy Systems & CHH[13]

1.6 Australia's energy use - 2030 and beyond

1.6.1 Overall energy use

According to the Australian Energy Resource Assessment (AERA) report[14], Australia's total energy demand is expected to continue to increase over the period to 2030, but at a slower rate than at present. This reflects the long-term trend in the Australian economy toward less energy intensive sectors and energy efficiency improvements, both of which can be reinforced by policy responses to climate change. The contributions of natural gas and renewables are expected to increase significantly.

Australia's primary energy consumption (heat, power, liquid fuels) is projected to increase from 5,772 PJ in 2007-08 (see Figure 1-9) by an average of 1.4 per cent per year to reach around 7,715 PJ by 2029–30. The primary fuel mix is expected to change significantly over this period, with the share of coal expected to decline to 23 percent and the share of natural gas expected to rise to 33 percent. In the AERA report, renewable energy is projected to account for 8 percent of Australian energy consumption by 2029–30 (see Figure 1-10). This chart indicates that in 2029-30 bioenergy would provide 4.4 percent of the national total, or 340 PJ of all primary energy use, requiring an average growth rate of 2.2 percent from 2007-2008 to 2029-30.

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[13] Bioenergy Australia 2010 conference presentation, S. Schuck, 2010.

[14] Geoscience Australia and ABARE, 2010, Australian Energy Resource Assessment, Canberra.

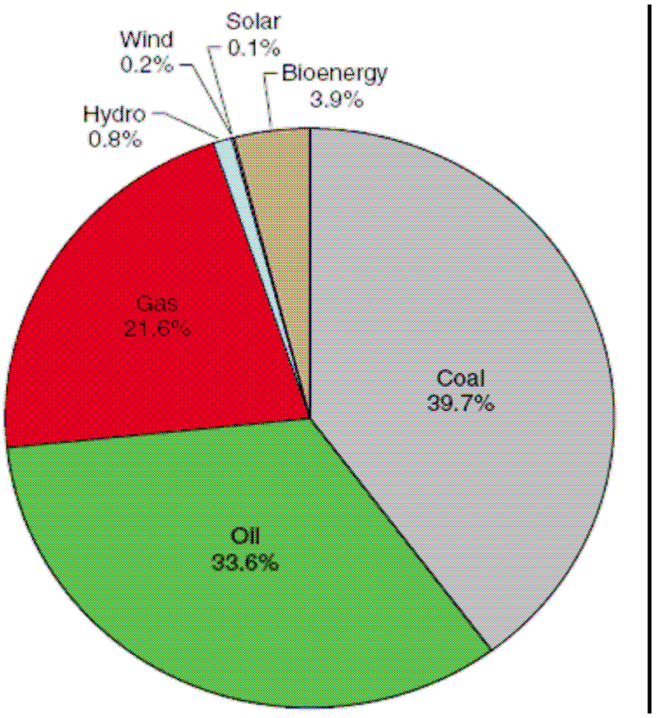

Figure 1-9 Australia's primary energy consumption 2007-2008 (5,772 PJ)

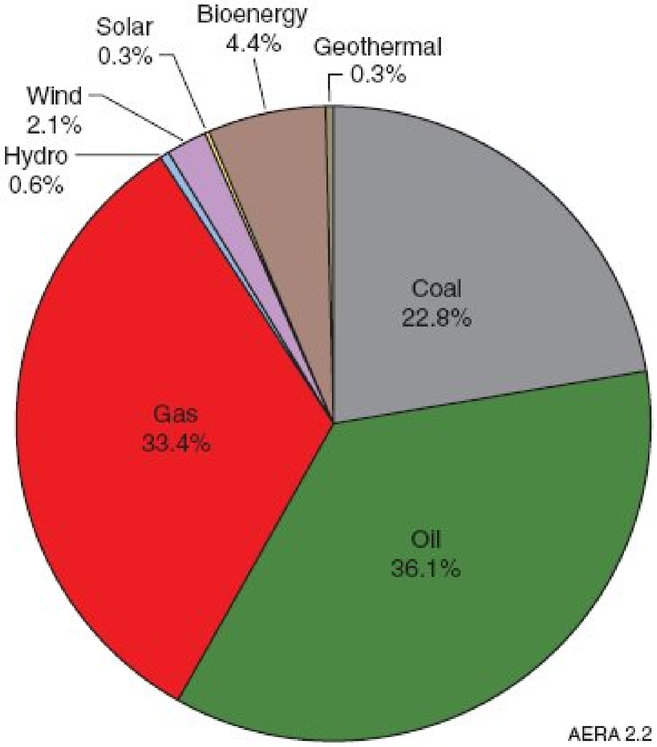

Figure 1-10 Australia's projected primary energy consumption 2029-2030 (7,715 PJ)

1.6.2 Electricity

Figure 1-11 below is taken from the AERA report and shows recent electricity generation from bioenergy in Australia and a projected figure for 2029-30.

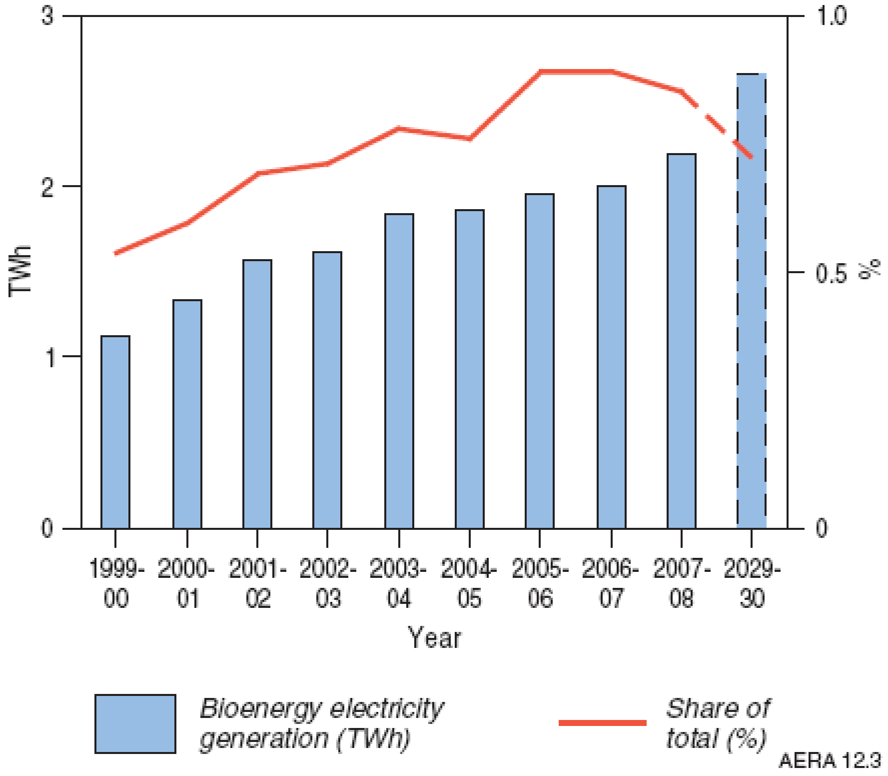

Figure 1-11 Electricity generation from bioenergy in Australia

Bioenergy for electricity generation is projected by ABARES to grow by 2.3 per cent per year over the period 2007-08 to 2029–30. In a more optimistic projection than the AERA report, the Clean Energy Council's 2008 Bioenergy Roadmap for stationary power generation[15] estimated that by 2020 biomass to electricity could supply 10,624 GWh/y (38.2 PJ/y), which is a fourfold increase over the production in 2008.

The Roadmap also indicated that by 2050 stationary biomass power plants could contribute 73 TWh/y (263 PJ/y) of electricity, which is about seven times the size of the 2020 target. This potential contribution is broadly in line with the 2004 *Clean Energy Future for Australia* report[16] that anticipated bioenergy contribution to electricity generation of 68 TWh/y in 2040. Table 1-6 shows the elements of the Roadmap's 2020 target and the 2050 projection.

This long-term potential placed the Roadmap's 2020 target as the first step in a journey that could deliver a very significant contribution to Australia's stationary energy future. In 2006 the Australian Business Roundtable on Climate Change[17] separately estimated that bioenergy could supply between 19.8 and 30.7 percent of Australia's electricity by 2050, again reinforcing the significant role bioenergy can play in meeting Australia's future energy needs.

The CSIRO has studied the prospects for large scale, sustainable bioenergy production in Australia, focussing on supply of biomass feedstocks. Preliminary CSIRO estimates show that a range of feedstocks including bagasse, crop stubble, plantations, urban wood waste, and short rotation energy crops could collectively provide 55.2 TWh/y (199 PJ/y) by 2030[18]. This equates to approximately 20 percent of current electricity production. See Figure 1-12.

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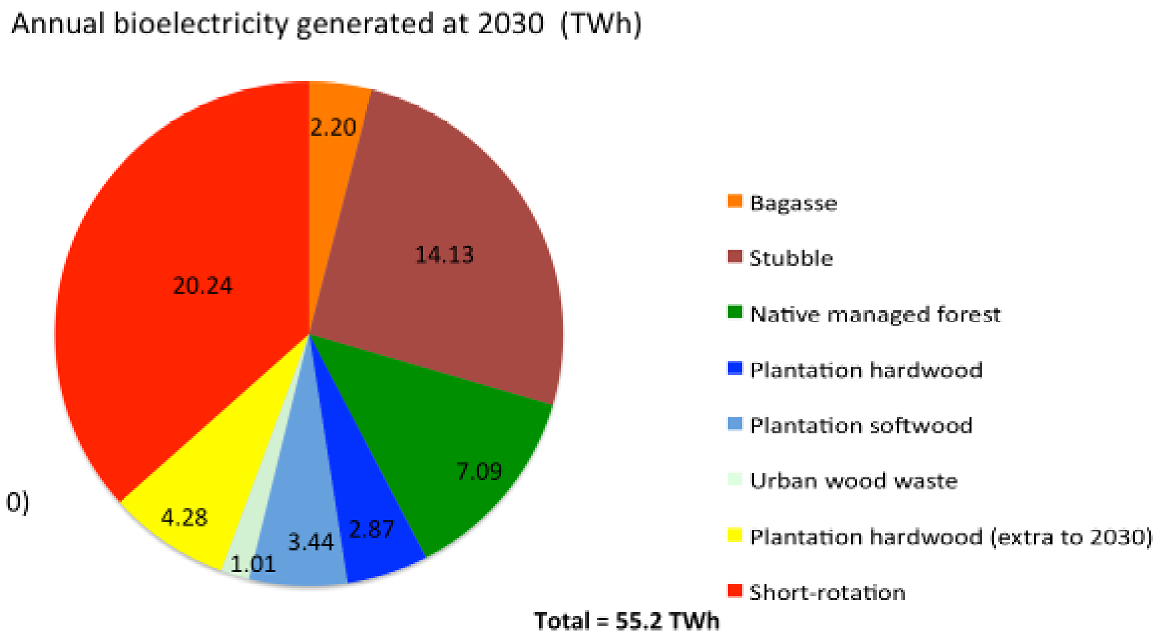
[15] Clean Energy Council, 2008
[16] Clean Energy for Australia report, WWF, 2004
[17] Australian Business Council on Climate Change, The Business Case for Early Action, 2006
[18] Bioenergy Australia 2010 conference presentation, Deborah O'Connell also as Farine et al, National Assessment of Opportunities for Bioenergy and GHG Mitigation in Australia. GCB Bioenergy Vol.4 issue 2 pp 148-175, March 2012

Table 1-6 **The Bioenergy Roadmap's target for electricity generation by 2020 and long term potential (2050)**

Resource	2020 Target GWh	Long Term Potential (2050) GWh
Sugarcane	3,165	7,800
Wood-related wastes	2,948	5,060
Landfill gas	1,880	3,420
Sewage gas	901	929
Agricultural-related wastes	791	50,566
Urban biomass (including urban timber wastes)	721	4,320
Energy crops	218	534
Total	10,624	72,629

Source: CEC Bioenergy Roadmap 2008



55.2 TWh/y ~ 20% current electricity production

Figure 1-12 **Projected bioelectricity production at 2030**

1.6.3 Biofuels

In its 2011 report for the Australian Government[19], the consultants LEK noted that Australia currently consumes 51 gigalitres of liquid fuels, and this volume is expected to grow to 67 GL by 2030, as shown in Figure 1-13.

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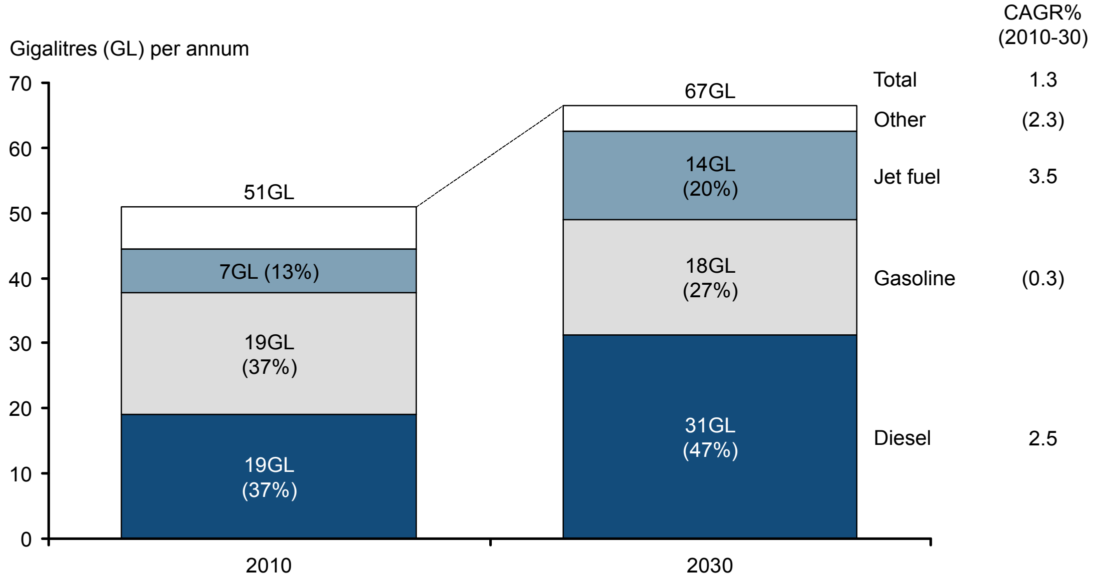
[19] Advanced Biofuels Study: Strategic directions for Australia. LEK, December 2011 http://www.arena.gov.au/_documents/abir/Advanced-Biofuels-Study.doc

It is feasible that a large proportion of this future demand could be met by biofuels, particularly those that use biomass as feedstock. A variety of technologies are under development for conversion of biomass into biofuels (see Chapters 17& 18) and assessments of Australia's capability to supply sustainable biomass show significant potential:

The biomass resource identified in the CSIRO work above could be used to produce electricity but it could also be used for biofuel production. For example, if all the biomass identified by CSIRO was utilised to make to ethanol, 13.7 GL/y ethanol (equivalent to 9.4 GL/y of petrol) could be produced. The CSIRO study also investigated potential biodiesel production in 2030 and found that 5.7 GL/y biodiesel could be produced in Australia, equivalent to more than 30 percent of current diesel fuel consumption. Much of this projection is based on commercialisation of biofuels from algae, which could be grown with resources that are additional to the biomass resources identified for electricity, ethanol or drop in biofuels.

Bartle *et al*[20] have considered biomass production from new woody crops (such as mallee eucalypts) in the Australian wheatbelt. They modelled woody crops grown in parallel with grain and livestock activities, with new woody crops using just 1.5% of farmland in the 300-400 mm rainfall zone, and 8% of farmland in the 401–600 mm rainfall zone of the Australian wheatbelt. Such a scenario is expected to produce 39.5 million tonnes/year of dry biomass. Based on yields of approximately 300 litres of diesel equivalent biofuels from each dry tonne of biomass, these new woody crops could be used to produce a theoretical maximum of 12 GL/y of liquid transport fuels.



Source: ABARES; CSIRO; L.E.K. research, interviews and analysis

Note: CAGR = compound annual growth rate

Figure 1-13 Fuel demand in Australia (current versus future)

The biomass resource bases indicated in the Clean Energy Council's Bioenergy Roadmap, and the studies by the CSIRO and Bartle *et al*, and also underpinned by the projections of the Australian Energy Resource Assessment report indicate that, in the longer term, bioenergy could make a substantial contribution to power, thermal energy and liquid fuels in Australia.

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[20] Scale of biomass production from new woody crops for salinity control in dryland agriculture in Australia, Int. J. Global Energy Issues, Vol. 27, No. 2, 2007

2. Introduction – biomass to energy

Bioenergy - for heat, power and liquid fuels – is the subject of considerable interest and activity world-wide. Drivers for bioenergy include:

- the reduction of CO2 emissions via the substitution of bioenergy for fossil fuels
- security of energy supplies
- regional employment and development, especially through new rural industries
- potential health benefits such as reduced particulate emissions.

Bioenergy may have a significant role in a low-carbon energy future:

- Biofuels feature as a source of both electricity and liquid fuels in carbon reduction scenarios modelled in 2008 by the CSIRO[1].
- Referring to electricity production to 2020 and beyond, the Clean Energy Council of Australia states: "*Bioenergy has a vital role to play as part of Australia's clean energy future*"[2].
- After studying the role for biofuels as a future transport fuel in Australia, the Australian Academy of Technological Sciences and Engineering (ATSE) stated: "*The key finding of this report ... is that biofuels…have useful roles to play as Australian transport fuels and can contribute to greenhouse gas mitigation and energy security*."[3]
- Overseas, the US Government's Roadmap for Bioenergy and Biobased Products[4] states: "Biomass resources are a sustainable and environmentally friendly feedstock that can contribute significantly to a diverse energy portfolio."
- The European Union's position is similar: "In the face of Europe's increasing dependency on fossil fuels, using biomass is one of the key ways of ensuring the security of supply and sustainable energy in Europe."[5]

But bioenergy is a complex topic:

- It encompasses multiple feedstocks from agriculture, forestry, and urban sources.
- It includes many different technologies: some widely used for decades, others only recently commercialised or still at the laboratory stage.
- Energy products include electricity, heat and liquid fuels. In the future it is possible that co-products will also feature in many bioenergy projects.
- As with most other forms of renewable energy, it involves the use of fossil fuels for its production, however the emissions resulting are often minor compared to the net GHG benefits derived over the entire lifecycle of bioenergy.
- It is the subject of active R&D world-wide, with a number of new technologies and feedstocks expected to be commercialised over the next decade.
- In some situations bioenergy may compete for feedstocks and land that would otherwise be used for food production.
- In other situations, new tree crops for bioenergy may enhance agricultural activities, through salinity mitigation, soil protection and increased biodiversity.

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1 Modelling the future of transport fuels in Australia by Graham et al, IR 1046, June 2008

2 Australian Bioenergy Roadmap - http://www.cleanenergycouncil.org.au/bioenergy/

3 Biofuels for Transport: A Roadmap for Development in Australia., by ATSE, November 2008

4 Executive Summary of Roadmap for Bioenergy and Biobased Products in the United States, by Biomass Research and Development Technical Advisory Committee, October 2007

5 http://europa.eu/legislation_summaries/energy/renewable_energy/l27014_en.htm

- There are high associated costs to commercialise new technologies and market barriers to the introduction and use of new fuels.

2.1 Biomass and bioenergy

Biomass is organic matter originally derived from plants, produced through the process of photosynthesis, and which is not fossilised (such as coal). Biomass can act as a store of chemical energy to provide heat, electricity and transportation fuels, or as a chemical feedstock for bio-based products.

Biomass resources include wood from plantation forests, residues from agriculture and forestry, and organic waste streams from industry, livestock, food production, and general human activities. Just some examples are wood chips, sawdust, cotton ginning trash, nut shells, straw, manure and human sewage. This study has focused principally on biomass from trees and then agricultural crops. Other sources of biomass, such as animal and human wastes, are not considered here.

Biomass for energy is a unique form of renewable, solar energy. Of the massive 178,000 x 10^{12} Watts of solar energy that falls on the Earth's surface, some 0.02% or 40 x 10^{12} Watts is captured by plants via photosynthesis and bound into biomass energy. This translates into the production of some 220 billion dry tonnes of biomass per year, which as an energy source represents many times the world's total current energy use. Approximately 10 percent of the planet's energy requirements are currently met from biomass, mainly for cooking and heating in developing countries, but also increasingly for fuelling a growing number of large scale, modern biomass energy plants in industrialised countries.

Bioenergy is essentially renewable and carbon neutral. Carbon dioxide released during the energy conversion of biomass (such as combustion, gasification, pyrolysis, anaerobic digestion or fermentation) circulates through the biosphere, and is reabsorbed in equivalent stores of new biomass through photosynthesis.

Bioenergy plants can range from small domestic heating systems to multi-megawatt industrial plants requiring several hundred thousand tonnes of biomass fuel each year. There are also a variety of technologies to release and use the energy contained in biomass, ranging from combustion technologies that are well proven and widely used around the world for electricity generation, to emerging technologies that convert biomass into liquid fuels for road, sea and air transport.

2.2 Background to study

This report has been commissioned by Bioenergy Australia[6], a national alliance of organisations involved in Australia's bioenergy industry. Bioenergy Australia was formed in 1997 to foster and facilitate the development of biomass for energy, liquid fuels, and other value added bio-based products. It now has more than 70 member organisations from government, academia, research institutes and industry. Bioenergy Australia is concerned with all aspects of biomass and bioenergy, from production through to utilisation, and its work embraces technical, commercial, economic, societal, environmental, policy and market issues.

Bioenergy as electricity, liquid fuels and heat, could grow significantly from its present base and provide sustainable energy, new industry and employment, across urban and rural Australia. However, the extremely varied nature of biomass, and the many routes possible for converting the resource to bioenergy, can make the whole topic of biomass to energy a complex subject. For energy from wind, solar and hydro the conversion technology is the key component, whereas for biomass the whole system needs to be considered. This entails gaining an understanding of diverse biomass resources; how to cost-effectively process and deliver these resources in a useful form to the conversion plant; how biomass can be transformed into heat, electricity, or both in a co-generation plant, or how biofuels can be used in road, sea, rail or air transport. The use of biomass for building and construction materials (to displace the higher energy-containing steel, aluminium or concrete) or as a chemical feedstock (as a substitute for petro-chemicals) is largely beyond the focus of this report.

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[6] http://www.bioenergyaustralia.org

2.3 So what is biomass?

From a renewable energy perspective, biomass can be defined as:

Recent organic matter originally derived from plants as a result of the photosynthetic conversion process or from animals and which is destined to be utilised as a store of chemical energy to provide heat, electricity, or transport fuels.

Biomass resources include wood from plantation forests, residues from agricultural or forest production, and organic waste by-products from industry, domesticated animals, and human activities.

The chemical energy contained in the biomass is derived from solar energy using the process of photosynthesis. (Photo means to do with light and synthesis is the putting together). This is the process by which plants take in carbon dioxide and water from their surroundings and, using energy from sunlight, convert them into sugars, starches, cellulose, lignin etc which make up vegetable matter loosely termed carbohydrates (and shown for simplicity as [CH2O]). Oxygen is produced during photosynthesis and emitted to the atmosphere.

$$\mathrm{CO2 + 2H2O} \xrightarrow[\text{Heat}]{\text{Light}} \mathrm{([CH2O] + H2O) + O2}$$

All plant matter on Earth, both terrestrial and marine, is formed using this process. Animals that consume plant material and even carnivorous species all depend directly or indirectly on photosynthesis. Thus many animal products and wastes can also be classified as forms of biomass if used for energy purposes. Only a very small portion of the solar radiation reaching the Earth is used for photosynthesis (Figure 2-1).

Worldwide, photosynthesis produces approximately 220 billion tonnes (dry weight) of biomass per year. As an energy source, this represents many times the world's current total energy use.

2.4 Biomass fuels

Fuels resulting from biomass may be any solid, liquid or gaseous fuel produced from a wide range of organic raw materials, either directly from plants or indirectly from industrial, commercial, domestic, forest or agricultural wastes. These cover a very wide range of energy sources and scales (Table 2-1), from simple firewood for small domestic fires to 500,000 tonnes of sugar cane residue (bagasse) a year used to fire a 50MW co-generation plant at a sugar mill.

The larger the project then usually the less the investment cost in terms of $/MW installed capacity. If the biomass is already collected on site, as in the case of wood process residues from a sawmill, then the size of bioenergy plant is usually limited by the lesser of the available resource or the onsite energy demand. Where the biomass is brought to a centrally located plant, the transport distance and corresponding cost of the feed may be a limiting factor to the commercially viable size of bioenergy plant.

While they are not considered in any detail in this report, waste-to-energy processes are also included under the general term "biomass" as they mainly consist of what were originally plant or animal products derived from their use for purposes other than for energy (e.g. paper, packaging, pallets). Urban, commercial and industrial wastes, sometimes classed as municipal solid wastes or "MSW", can have the inorganic and non-combustible fractions (e.g. glass and metal) removed, leaving mainly waste of biological origin – apart from the plastic component which is fossil fuel derived but also combustible.

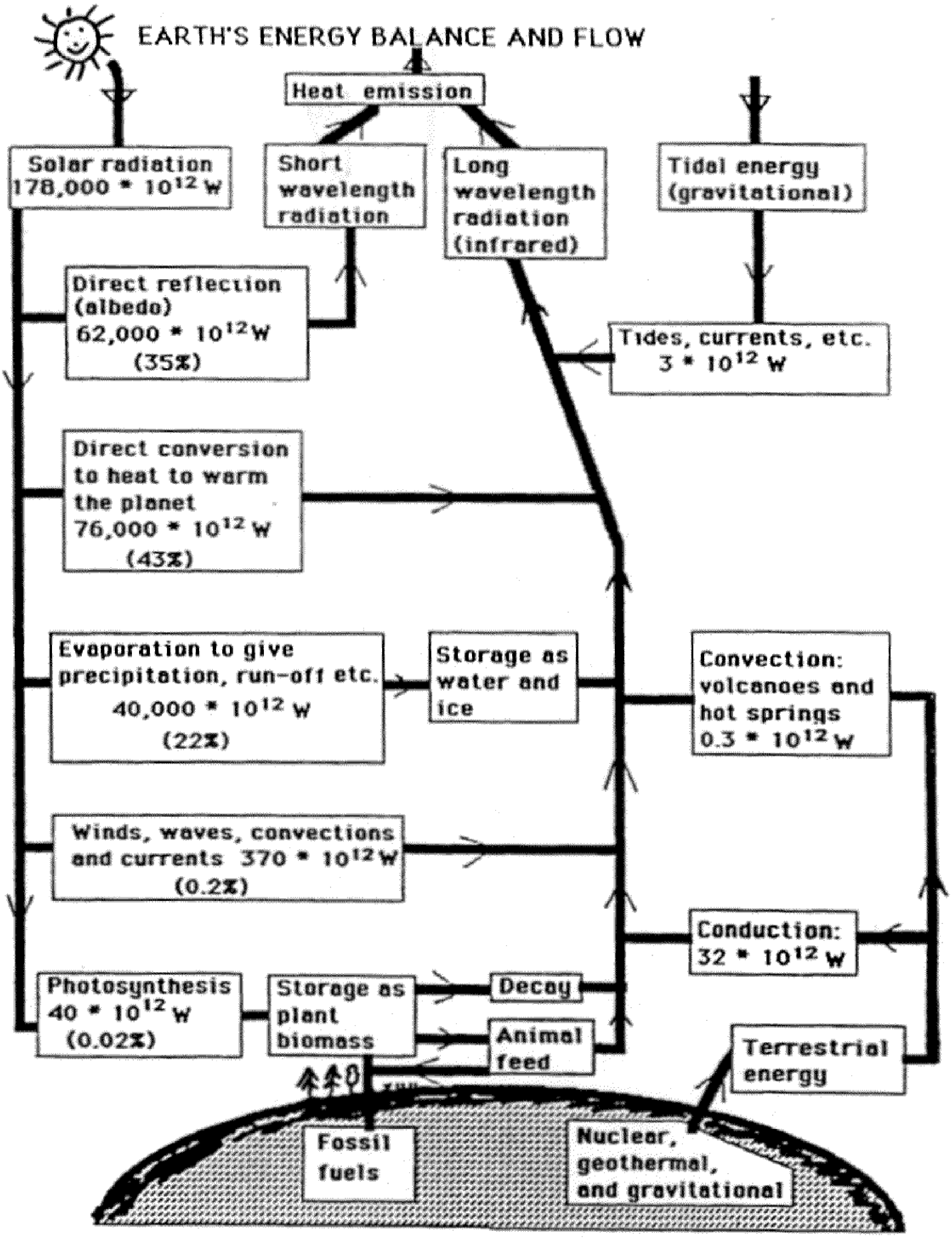

Figure 2-1 The Earth's energy flows are in balance

(Most of the Earth's energy supply comes from the sun but due to continuous heat losses to space, the Earth's energy flows are in balance.)

Combustion of fuel with atmospheric oxygen provides energy as heat. Natural decomposition of biomass is also an oxidation process, but the chemical energy is released as heat much more slowly. Both processes produce carbon dioxide and water. But that is not the end of the process, as nature completes the cycle putting energy (from the sun) back into these end-products via growing plants to create more biomass fuel and oxygen.

Table 2-1 An indication of the relative scales of energy conversion plants using biomass fuels and a comparison with fossil fuel power plants

Size	Properties served	Annual fuel demand	Vehicle movements	Conversion technology	Physical size	Investment cost
Domestic heating (15kWt)	Family dwelling	3 - 5 odt* wood	2 - 3 tractor loads /y	Boiler or wood burner	Large suitcase	$ 100s
Small business heating (350kWt)	School or small factory	80 – 120 odt wood or straw	40 tractor loads /y	Boiler or straw burner and fans	Garage for one car	$ 10,000s
Small electricity generating plant (250kWe)	200 – 300 houses or small industry	1,500 – 2,000 odt wood or straw or wet wastes	6 x 20t trucks / week	IC** engine or gasifier	Small barn	$ 10,000s
Medium electricity generating plant (5MWe)	4,000-6,000 houses or small industrial estate	20 – 30,000 odt of range of biomass fuels	50 x 38t trucks / week	IC engine or steam turbine or gasifier	Petrol service station	$100,000s
Large electricity generating plant (30MWe)	25-35,000 houses or industrial estate	120-140,000 odt using dry biomass fuels	250 x 38t trucks / week	Steam turbine or gas turbine or combined cycle	Large church	$ millions
Combined cycle gas turbine or coal-fired station (500MWe)	500,000 houses or large industrial site	800 Mm3 gas or 1Mt coal	Pipeline Or 900 x 38t trucks / week equiv	Gas turbine and / or steam turbine	Large barn or Sydney Opera House	$ millions

** odt = Oven Dry Tonnes*

***IC = internal combustion engine*

[Source: Wood Fuel from Forestry and Arboriculture, Department of Trade and Industry & ETSU, July 1999].

Some materials will burn and others, such as sand and water, will not. Combustion of a fuel needs oxygen to chemically react the carbon and hydrogen containing molecules of the fuel. Heat is produced. Therefore a fuel can be defined as a substance that interacts with oxygen, changes chemically, and thereby releases its stored chemical energy.

For example, methane (CH_4), a common fuel as contained in natural gas, biogas, and landfill gas, reacts with oxygen (O_2) as follows:

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O + \text{energy}$$

This chemical reaction typifies the burning of any common fuel: a compound containing carbon and hydrogen interacts with oxygen (usually from the air, though there are cases when pure oxygen is used) to produce carbon dioxide and water.

Chapter 3 of this report considers the combustion properties of biomass feedstocks.

2.5 Biomass for renewable energy and greenhouse gas mitigation

Scientists are now confident that an enhanced greenhouse effect is occurring and that a substantial part of the observed change in climate is due to human activities[7,8]. Fossil fuels are abundant and projections from the World Energy Council suggest that oil, coal and gas should all be available throughout most of this century and that they will remain the dominant energy source for the foreseeable future.

As a response, carbon dioxide emissions to the atmosphere can be reduced by:

- lowering the levels of energy services
- providing energy or consuming energy services via more efficient technologies and systems thereby reducing energy intensity
- switching from fossil fuels to renewable sources of energy, including biomass, or to nuclear energy, or switching from higher carbon fuels (e.g. coal) to lower carbon fuels (e.g. natural gas)
- removing carbon from fuels and combustion exhaust gases or from the atmosphere and storing it in some way in perpetuity (sequestration).

Biomass is a renewable energy resource that results in a negligible net contribution of CO_2 to the atmosphere. Plants during growth take up CO_2, which is later released during bioenergy processes. Where agricultural land is transferred to energy crop production, a net uptake of CO_2 also often results from the increased ‘carbon density’ of the land use and possibly in the soil too. Other forms of biomass utilisation, such as landfill gas or the collection of forest residues otherwise left to decompose on the forest floor, can also reduce the release of methane (a more potent greenhouse gas) into the atmosphere.

Biomass has the dual advantage of acting as an energy substitute for fossil fuels (a carbon offset) and also as a means of sequestering carbon (a carbon sink). Hence it is recognised widely that bioenergy will play an important role in the objectives of the United Nations Framework Convention on Climate Change (UNFCCC). An excerpt from the International Energy Agency Bioenergy News best sums up the potential of using bioenergy.

Modern bioenergy options offer significant, cost-effective and perpetual opportunities toward meeting emission-reduction targets while providing ancillary benefits. Moreover, via the sustainable use of the accumulated carbon, bioenergy has the potential for resolving some of the critical issues surrounding the long-term maintenance of biotic carbon stocks. Finally, wood products can act as substitutes for more energy-intensive products, can constitute carbon sinks, and can be used as biofuels at the end of their lifetime [9].

CO_2 emissions can be reduced by approximately 97% and 93% when suitable biomass is combusted for electricity generation and substitutes for coal or gas respectively. However, the use of more efficient bioenergy conversion systems such as gasification, can further improve emission reductions.

2.6 So what is bioenergy?

A number of conversion routes exist to change biomass into useful forms of energy, as shown in simplified form in Figure 2-2.

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[7] http://www.metoffice.gov.uk/climatechange/
[8] http://www.ipcc.ch/
[9] IEA, 1998

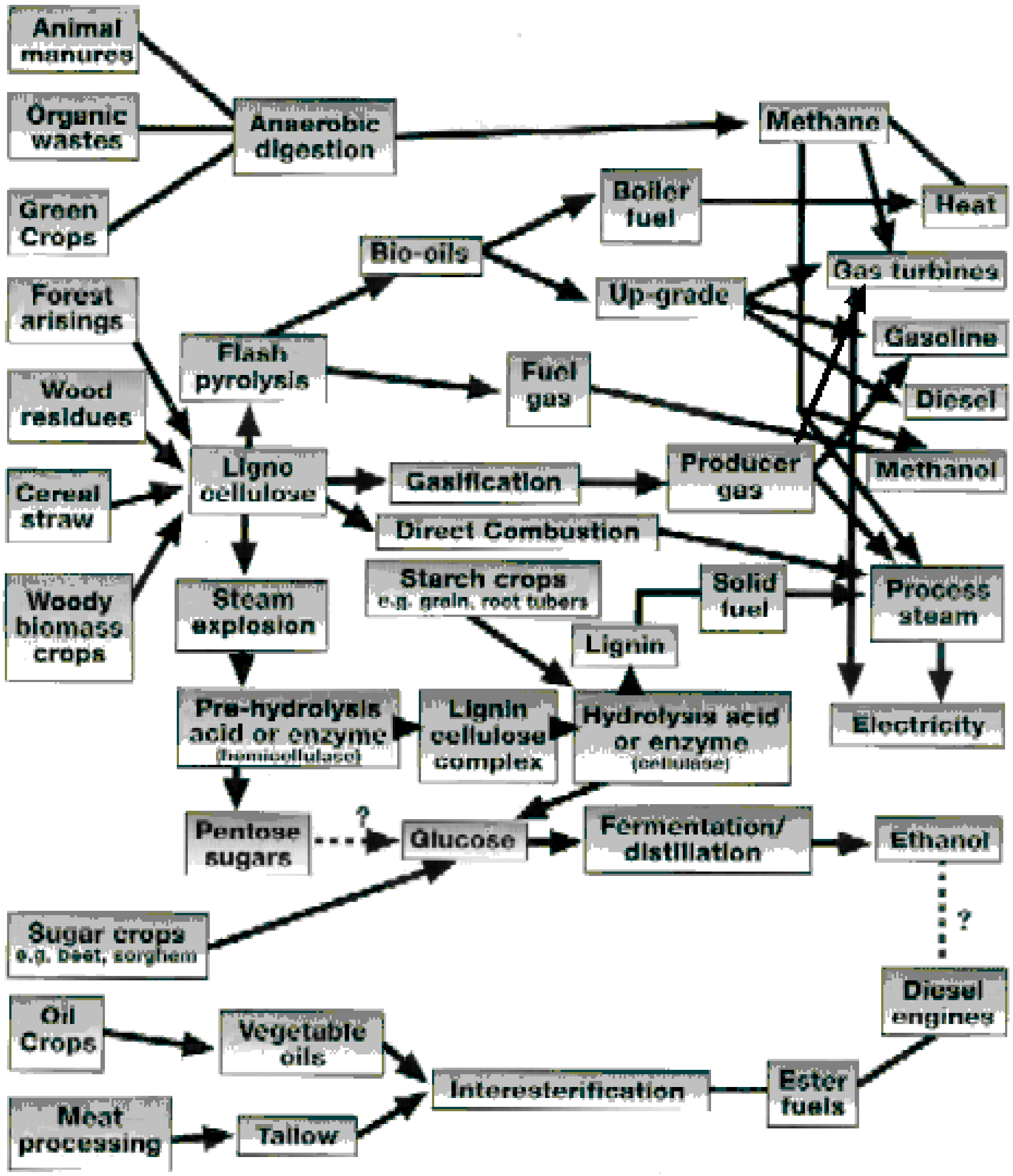

Figure 2-2 **Some routes for converting a number of different biomass materials into useful energy products**

Many of these will be covered in detail in later chapters of this report. The owner of a biomass resource can collaborate with a project developer to convert that resource into useful energy projects in order to maximise the return on investment. Where the resource is a waste product, avoiding any treatment or disposal costs can lead to dual benefits, or a “win/win” opportunity.

The biomass conversion routes have a major impact upon whether or not a project is commercially viable and the costs for these conversion processes are often very site and project specific. They vary with the source of raw biomass, its moisture content, the transport distance, the complexity of the process involved, the plant scale, the value of any co-products, the savings of disposal cost if a

waste, the reduction in greenhouse gas emissions, the market value for the bioenergy, and whether there are subsidies and incentives available. Careful analysis and risk assessment are therefore required to get a good overview of what is involved and the chance of commercial success for each project. These activities are considered further in Attachment 4:
The project development pathway.

Costs for many bioenergy plant options can be determined by working with experienced engineers or equipment suppliers, and the more accurate the data provided, the more accurate will be the estimates of project costs.

It is expected that costs for many bioenergy technologies will reduce over time as industry knowledge increases with regard to feed materials, processing scale and efficiencies, and operating characteristics in commercial plants. It is possible to learn from projects already in place. As for any technology, bioenergy should progress steadily down the experience curve as a result of "learning by doing". In rough terms the installed cost of a plant will reduce by 20% for every doubling of the total installed capacity. Some bioenergy technologies such as wood combustion are relatively mature (though increased efficiencies are still being gained for little extra investment costs). Others, such as converting wood to liquid fuels, are still at the demonstration stage with potential for rapid cost reduction after commercial operations begin.

This report examines in some detail the various elements of bioenergy, from the nature of biomass as a fuel source, issues related to its production, harvesting and transport, its conversion into primary and secondary energy products and services, costs and economics of bioenergy in its various forms, and co-values and co-products associated with bioenergy.

2.7 A note on terminology

During the course of the study several different names were identified for groups of trees that would be harvested regularly in cycles of several years, as opposed to the cycle times of fifteen years or more. The latter times typically apply to plantations established for sawlogs or processing for other wood products. In defining these short cycle trees attention was given to whether the tree:

- is to be harvested in short "rotation" or short "cycle". In forestry the two terms are similar, however in agriculture rotation can be taken to mean a change of crop rather than a time for growth.
- is planted for energy alone or for energy and other uses. Unless the usage is specifically for energy for illustrative purposes (for example in the Australian case studies developed as part of this project) we have endeavoured to avoid the use of "energy", to promote the concept that crops planted for multiple products or purposes are more likely to be commercially viable than trees planted for energy alone.
- coppices (resprouts from the cut base after harvesting). We have endeavoured to avoid the term "coppice" as some tree species with potential for biomass and other uses do not coppice.
- is part of a plantation, forest or crop. There are no apparent distinctions between each word. We have endeavoured to use "crop" to focus on the difference between these short cycle trees and current use of "plantations" to describe stands of pine and blue gum.

This report therefore uses "short cycle (woody) crops" as its preferred terminology but also makes use of other, similar terms where it is felt appropriate.

3. Thermal properties of biomass feedstocks

3.1 Summary

Biomass from plants is characterised by a number of physical and chemical properties that require special consideration for its use as an energy source, particularly with the wide range of processes available for production of heat, electricity and liquid fuels. The main determinants of fuel properties are:

- **Moisture content**. Dry, ash free woody biomass typically has a heating value in a narrow range of 18-21 MJ/kg, irrespective of plant species. The moisture content of the biomass is actually the major determinant of the operational heating value. Biomass with higher moisture content will have lower energy content per unit weight. Boiler efficiencies are reduced by high moisture content in the biomass fuel. Biomass fuels can vary in moisture composition from less than 10 percent in cereal straw to more than 50 percent for freshly harvested wood. Moisture content needs to be carefully considered in the design and operation of a bioenergy combustion plant. Dry biomass burns much hotter than moist biomass; potentially placing different requirements on the materials of construction and the emission controls. Moisture content also influences the storage durability of biomass, as degradation and spontaneous combustion can result.
- **Ash content.** Ash is an inorganic, incombustible component of biomass, and is a major determinant of problems (fouling, slagging, corrosion and erosion) in many bioenergy plants. Ash is an inherent part of biomass that ranges from as little as 0.2 percent in tree species to over 20 percent in rice hulls. Ash is also derived from sand and soil absorbed in bark and dirt that may have been collected with the biomass feedstock. Some components of ash pose greater problems for energy plants than others however, in general terms, the lower the ash levels the better.
- **Volatile matter content.** Upon heating, biomass gives up a large fraction of its weight in the form of combustible gases. This volatile component of biomass can be as high as 80 percent for dry wood. Volatile matter determines the gas flows within boilers and gasifiers; a design parameter.
- **Elemental composition.** The principal components of plant biomass are carbon, oxygen and hydrogen. Carbon is the main constituent of biomass, making up 30-60 percent of its dry mass. As a fuel, biomass is highly oxygenated compared to conventional fossil fuels such as coal and petroleum products. Hydrogen generally makes up 5-6 percent of the biomass. Typically 37-45 percent of the mass of dry biomass is oxygen.

  Nitrogen, sulphur and chlorine are also present in biomass, generally at levels below one percent. These elements can be determinants of gaseous emissions from biomass power plants. Chlorine also plays a major role in corrosion mechanisms, and in the production of acid emissions. Various inorganic elements can also be found in biomass and have implications for the design and operation of the bioenergy plant, as they establish fouling, corrosion and erosion conditions during operation. Important inorganic elements in biomass feedstocks are alkali metals, most notably sodium and potassium and silica in grasses and straw. These are heavily implicated in fouling of boiler tubes and need to be controlled.
- **Heating Value.** Heating value does not vary significantly across various forms of woody biomass. An empirical formula for the (higher) heating value of dry biomass, based on the elemental composition of the biomass, is:

  $HHV_{d.b.} = 0.3491{*}C + 1.1783{*}H + 0.1005{*}S - 0.0151{*}N - 0.1034{*}O - 0.0211{*}Ash$ [MJ/kg][1]

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[1] Channiwala SA, On biomass gasification process and technology development – some analytical and experimental investigations. Ph.D thesis, Mechanical Engineering Department, The Indian Institute of Technology, Bombay, 1992.

The formula works reasonable well for all biomass, including non-woody biomass.
The operational heating value declines linearly with increasing moisture content.

- **Bulk density and particle size.** The density of biomass fuel determines much of the economics of fuel transportation and storage. The energy density (energy per unit volume) of biomass fuels can be as low as one twentieth that of fossil fuels. For instance planer shavings can have a bulk density of a mere 97 kg/m^3. This requires plant and equipment to cater for high volumes of biomass per unit of energy output.

In general, bioenergy plants can be readily adapted to specific fuel parameters through careful design and operating procedures. Guiding values for unproblematic utilisation of biomass fuels have been developed, and are presented in detail later in this chapter. If guiding values cannot be attained, then various technological solutions can often be applied to ensure trouble free operation of the bioenergy plant. For instance NOx emissions may be controlled through staged combustion (better mixing of oxygen and fuel), use of flue gas scrubbers, temperature control within the furnace and use of catalytic converters.

Note that design of an energy plant to operate on a particular feed does not mean that the plant will operate as well on other biomass fuels. Bioenergy plants designed to operate on a particular feed can experience major problems if different feeds are substituted for the original biomass. Good data on fuel properties during design, and consistent fuel during operation are very important for a successful bioenergy project.

A number of Australian organisations with experience and capability in analysing biomass fuels exist, confirming Australian capability with biomass fuels over several decades.

3.2 Biomass as a fuel

Biomass is the product of plant photosynthesis. Via photosynthesis, solar energy contributes to the chemical energy in the biomass and may be recovered by thermal processes such as combustion, gasification or pyrolysis. (This energy may also be recovered via fermentation of the sugars present in the biomass.)

As a fuel, biomass is highly oxygenated compared to conventional fossil fuels such as coal and hydrocarbon liquids. Typically 37-45 percent by weight of the dry matter in biomass is oxygen (O). Carbon, the principal constituent of biomass makes up 30-60 percent of the dry matter, depending on ash content. Hydrogen (H) is generally the third major constituent, comprising typically 5-6 percent of the dry matter. Nitrogen, sulphur and chlorine are also present and are usually well below one percent of dry matter, although on occasions they exceed this value. Various inorganic elements can also be found in biomass and they potentially have important implications for the design and operation of the bioenergy plant, as they establish the fouling, corrosion and erosion properties of the products of thermal processing. These elements include alkali metals, most notably sodium and potassium, and silica in grasses and straw. Of note, silica is the third largest component in rice straw, at 10-15% of dry matter.

The Van Krevelen diagram below (Figure 3-1) illustrates the chemical composition of biomass compared to other solid fuels. The high O/C and H/C ratios for biomass fuels are responsible for biomass fuels being more volatile than peat and coals, and the high O/C ratio results in biomass having lower heating values. The diagram also illustrates that biomass as a fuel is on a continuum with coals and peat.

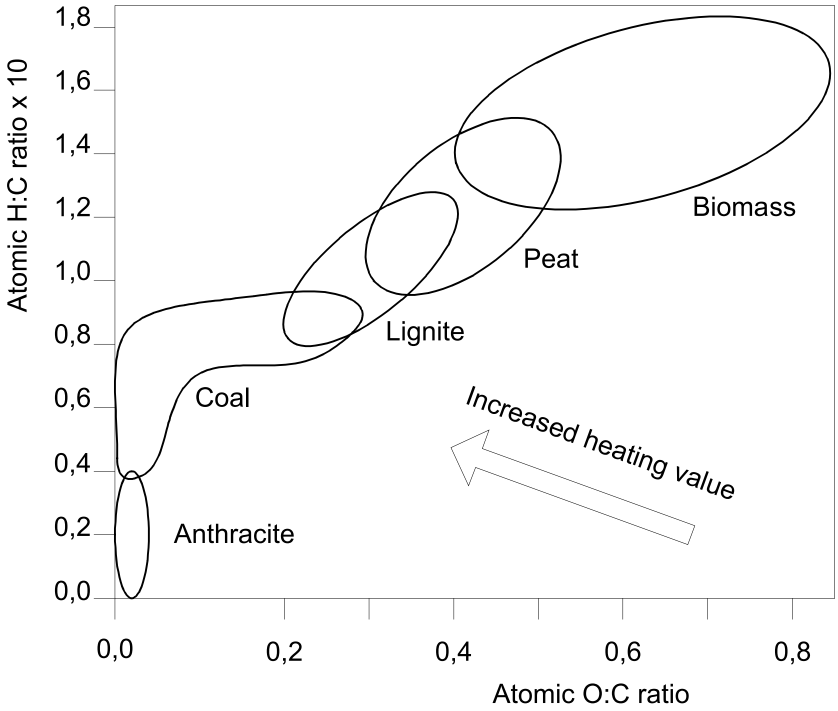

Figure 3-1 **Van Krevelen diagram for solid fuels** [2]

3.3 Determinants of fuel properties

The most important properties of biomass relating to their thermal energy conversion properties are:

- Moisture content
- Ash content
- Volatile matter content
- Elemental composition
- Heating value
- Bulk density and biomass particle size.

3.3.1 Moisture content

The moisture content of biomass is the quantity of water in the biomass, expressed as a percentage of the material's weight. This weight may be on a wet basis (wb), on a dry basis (db), or on a dry-and-ash-free (daf) basis. If expressed on a wet basis, the moisture content is expressed as a percentage of the sum of the total weight of the biomass (made up of the dry-and-ash-free matter, the water and the ash).

Moisture content is an important parameter. Increased moisture content reduces the energy content of the biomass (usually expressed in MJ/kg), and the remaining combustible material will also have more of its energy utilised to evaporate the water present. The design of bioenergy combustion plants needs to take the fuel moisture content into account, as dry biomass with its higher energy content will result in higher release of energy and can result in overheating and consequent damage to furnace components, while wet biomass with its lower energy content may require the combustion chamber to be insulated to maintain boiler efficiency and enable continuous combustion to take place

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[2] Baxter, L. Ash Deposition during Biomass and Coals Combustion. Biomass and Bioenergy, Vol 4, No. 2, 1993, Pergamon Press Ltd, pp. 85-102.

without the need for supplementary fuel. Knowledge and control of the moisture content range of the fuel can be very important, as biomass can have a wide range of moisture content (on a wet basis), ranging from less than 10 percent for cereal grain straw up to 50-70 percent for freshly harvested wood. Moisture content of the biomass will also impact on storage durability of the biomass, susceptibility to fungus and degradation, plant design, and potential for spontaneous ignition.

3.3.2 Ash content

The inorganic and incombustible component of biomass is termed ash, and can similarly be expressed as a percentage of the biomass weight. Usually ash content is expressed as a percentage on a dry basis. Ash is undesirable as some will exit the combustion chamber in the flue gas (fly ash), creating a need for capture and disposal. Ash is also the major determinant of fouling, slagging, corrosion and erosion of bioenergy power plant components.

Ash in biomass fuels comes from two sources. The inherent ash is an integral part of the biomass and consists of a wide range of chemical elements. Inherent ash can be as low as 0.2 percent for certain Australian tree species, 5 to 10 percent in diverse agricultural crop residues, and over 20 percent in rice hulls[3]. The other source of ash with the biomass is derived from sand and soil absorbed in the bark of trees and from dirt incorporated into the biomass during harvesting, handling and transportation.

The total ash content of the biomass and the chemical composition of the ash are both important to thermal bioenergy projects. The composition of the ash affects its behaviour under high temperatures of combustion and gasification. Primarily potassium (K) and partly sodium (Na) based salts in biomass result in “sticky” ash, which may cause deposits on boiler components. In addition, K and Na, in combination with chlorine (Cl) and sulphur (S), play a major role in corrosion. Biomass fuels with a molar S:Cl ratio below 2 can cause corrosion problems, because of the formation of significant amounts of alkali metal chloride salts. Furthermore, the volatilisation and subsequent condensation of volatile metals can lead to the formation of sub-micron fly ash particles (aerosols) which are difficult to precipitate in dust filters, form deposit layers on boiler tubes and can raise ecological and health risks. Accordingly, the lower the amounts of potassium and sodium salts in the biomass fuel, the better.

Heavy metal concentrations in biomass ashes are of considerable importance for ash utilisation and disposal. The ecologically-relevant elements are cadmium (Cd) and to a smaller extent zinc (Zn) if only untreated biomass is considered. Straw, cereals and grass ash contain significantly smaller amounts of heavy metals than wood and bark ash. This is explained by the longer rotation periods of wood, which allows heavy metal accumulation, the higher deposition rates in forests, and the lower pH value (acidic) of forest soils that increases the solubility of most of the heavy metals. Fortunately, biomass ash generally contains very low levels of toxic metals, and the ash can often be used as a soil amendment.

3.3.3 Volatile matter content

Upon heating (400°C to 500°C), biomass gives up a large fraction of its weight in the form of combustible gases. This requires combustion chambers to be designed to provide the combustion air where these gases are burned. The percentage of volatile matter on a dry basis in biomass typically ranges from 63 percent for rice hulls to over 80 percent for wood. By contrast, the volatile matter in bituminous coal, as used in NSW and Queensland, is under 20 percent. The high levels of volatile matter in biomass feed also have implications for gas flows within boilers and gasifiers.

3.3.4 Elemental composition

The elemental composition of biomass on a dry-ash-free basis is relatively uniform. Table 3-1 shows the elemental composition of some typical biomass feedstocks.

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[3] Jenkins, B.M., Baxter, L., Miles T.R. Jr, Miles T.R.. Combustion Properties of Biomass, in Proceedings of Biomass Usage for Utility and Industrial Power, Snowbird, Utah, 28 April to 3 May 1996.

Table 3-1 Elemental composition of typical biomass fuels

Component or Attribute		Pinus radiata	Eucalyptus globulus	Wheat straw	Rice hulls	Sugar cane bagasse
Carbon	C % d.b.	51.3	48.2	44.9	38.8	48.6
Hydrogen	H % d.b.	6.0	5.9	5.5	4.8	5.9
Oxygen	O % d.b.	42.6	44.2	41.8	35.5	42.8
Nitrogen	N % d.b.	0.11	0.39	0.44	0.52	0.16
Sulphur	S % d.b.	0.01	0.01	0.16	0.05	0.04
Chlorine	Cl % d.b.	0.01	0.02	0.23	0.12	0.03
Ash	ash % d.b.	0.33	1.1	7.02	20.3	2.44
Volatiles	% dry matter	81.8	81.6	75.3	63.5	85.6
Higher Heating Value	MJ/kg d.b.	20.3	19.2	17.9	15.8	19.0

Table 3-2 [4] illustrates in more detail the levels of nitrogen, sulphur and chlorine in a variety of biomass feedstocks, showing the higher nitrogen, sulphur and chlorine levels typical of several agricultural residues.

Table 3-2 Nitrogen, sulphur and chlorine compositions of biomass feedstocks

	Nitrogen (N) mg/kg (d.b.)	Sulphur (S) mg/kg (d.b.)	Chlorine (Cl) mg/kg (d.b.)
Wood chips	900 – 2,000	70 – 300	50 - 60
Bark	3,000 - 4,500	350 – 550	150 - 200
Straw (winter wheat)	3,000 - 5,000	500 - 1,100	2,500 - 4,000
Miscanthus	4,000 - 6,000	200 - 1,400	500 - 2,000
Triticale (cereals)	6,000 - 9,000	1,000 - 1,200	1,000 - 3,000
Hay	10,000 - 20,000	2,500	2,500 - 4,500
Needles (conifer)	12,000 - 15,000		
Grass	19,000 - 25,000	800	2,600

The chlorine level in the biomass is important as it plays a major role in corrosion mechanisms. It also determines levels of HCl (hydrochloric acid) emissions and is related to the formation of dioxins and furans. Chlorine levels in wood are generally very low at about 0.01 percent, but may be high in agricultural crops residues such as maize, where it can be as high as 1.5 percent on a dry basis. Chlorine levels in agricultural crops are to an extent dictated by chlorine levels in fertilisers. This may be controlled by using Cl-free fertilisers.

Fuel-bound nitrogen (N) is substantially responsible for the formation of NOx, an atmospheric pollutant, at combustion temperatures in the range 800°C to 1,100°C. The balance of NOx produced arises from nitrogen contained in the combustion air, and occurs at combustion temperatures above 950°C. NOx can be limited by controlling the use of N supplied with fertilisers and by using low combustion temperatures and staged combustion.

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[4] Obernberger, I. Biomass and Bioenergy, Decentralised Biomass Combustion: State of the Art and Future Development, Vol. 14, No. 1, 1998, page 33-38.

3.3.5 Heating value

The heating value of a fuel is an indication of the energy chemically bound in the fuel. A measure of this heating or calorific value is the gross or higher heating value (HHV), which includes energy used to evaporate moisture of the biomass during thermal conversion.

The higher heating value[5] (HHV, MJ/kg, d.b.) of woody biomass fuels does not vary significantly. It usually varies between 18 and 21 MJ/kg (d.b.), and can be calculated reasonably well by using the empirical formula [6].

$$HHV_{d.b.} = 0.3491*C + 1.1783*H + 0.1005*S - 0.0151*N - 0.1034*O - 0.0211*Ash \quad [\text{ MJ/kg}]$$

where C,H,S,N,O, Ash are the content of carbon (C), hydrogen (H), sulphur (S), nitrogen (N), oxygen (O) and ash in wt % (d.b.). As can be seen from the formula, the content of C, H and S contributes positively to HHV, while the content of N, O and ash contributes negatively to the calorific value.

The lower heating value[7] (LHV) discounts the energy included in evaporating the moisture, including that formed from the chemical conversion of the hydrogen in the fuel to water. The operational, or as received (ar) HHV and the LHV are given by the formulae [8]:

$$HHV_{ar} = HHV_{d.b.}(1-w/100)$$

$$LHV_{ar} = HHV_{ar} - 2.442\{8.936H/100*(1-w/100) + w/100\}$$

where w is the moisture content, expressed as a percentage on a wet basis. The above two formulae show that there is a double effect of moisture on heating values. Moisture reduces the amount of combustible material in each kilogram of biomass and, if the heat of evaporation is not recovered, the available energy of the fuel is further reduced through the energy required to evaporate the moisture in the fuel. Moisture content is therefore a major determinant of the operational heating value of biomass fuels, which will typically be 9.7-11.7 MJ/kg for fresh wood chips and 14.8-15.8 MJ for wheat straw [9].

For an accurate assessment of the energy that may be usefully recovered from a fuel, it is important to be quite clear as to moisture content (including its potential variations) and whether the heating values being discussed are HHV or LHV.

Figure 3-2 below is indicative of the variation in heating values with moisture content.

3.3.6 Bulk density and biomass size

Density refers to the weight of the biomass per unit volume. Bulk densities refer to the overall density when pieces of biomass (chips, sawdust, off-cuts, branches etc) are collected together. Biomass bulk densities tend to be low compared to conventional fossil fuels such as coal. This lower density, taken together with biomass' lower energy per unit of mass gives biomass an energy density (energy per unit volume), that is only approximately one-tenth that of fossil fuels such as high quality coal. On a dry-ash-free basis, bulk densities of different types of biomass can themselves vary significantly as shown Figure 3-2[10].

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[5] Also called "Gross Heating Value"

[6] Gaur, S. & Reed, T.B. An Atlas of Thermal Data for Biomass and Other Fuels, NREL/TB-433-7965, UC Category:1310, DE95009212.

[7] Also called "Net Heating Value"

[8] PHYLLIS database of biomass compositions, www.ecn.nl/phyllis/defs.html

[9] Wood for Energy Production, Technology-Environment-Economy, The Danish Centre for Biomass Technology, second edition, 1999, p31. ISBN 87-90074-28-9.

[10] Biomass Conversion Technologies, European Commission, EUR 18029 EN, Nov 1998, page 37.

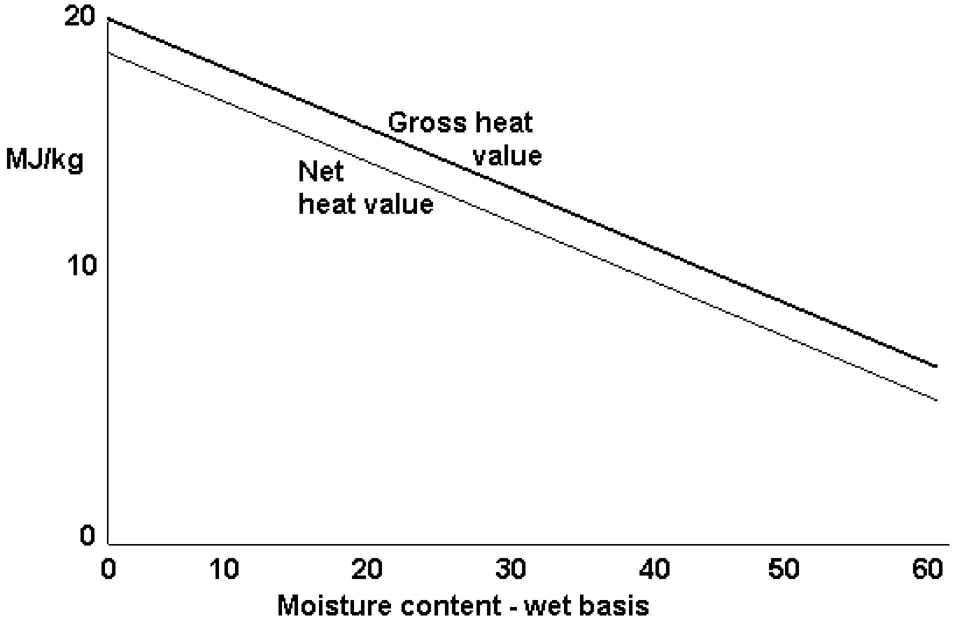

Figure 3-2 Variation of heating values with moisture content for typical biomass fuel

Table 3-3 Bulk densities of various biomass fuels

Biomass Type	Bulk Density (kg/m^3 daf)
Wood	
• Hardwood chips	227
• Softwood chips	179-192
• Pellets	556-625
• Sawdust	161
• Planer Shavings	97
Straw and stover	
• Loose	20-40
• Chopped	20-81
• Baled	111-204
• Moduled	97-1250
• Hammermilled	20-101
• Cubed	323-667
• Pelleted	556-714
Orchard Prunings - hammermilled	141-204

The implication for biomass transportation and storage, and for energy conversion, is that designs of plant and equipment need to cater for the high volumes of biomass per unit of energy output. Feed systems need to be appropriately designed for bulk handling of the biomass. Fine biomass particles and volatile organic matter in fuel piles are susceptible to being lost during transportation and storage.

3.4 Guiding values for biomass fuels

Obernberger [11] has developed guiding values for biomass fuels and biomass ashes to help avoid problems during thermal conversion of biomass fuels. These values are presented in Table 3-4 below. The table also suggests technological solutions if the guiding values are exceeded. In general, bioenergy plant designs can readily be adapted to the fuel parameters. Organisations in Denmark in particular have used agricultural straw for Combined Heat and Power plants with great success. The fuel requirements, as indicated Table 3-4 can be accommodated in the plant designs.

Table 3-4 Guiding values for unproblematic utilisation of biomass fuels

Element	Guiding concentration in the fuel (wt % on d.b.)	Limiting parameter	If guiding concentration ranges are not kept, problems can occur for:	Technological alternatives if the guiding ranges are not fulfilled
N	< 0.6	NO_x emissions	Straw, cereals, grass	Primary measures (air staging, reduction zone)
	< 2.5		Waste wood, fibre boards	Secondary measures (SNCR or SCR process)
Cl	< 0.1	Corrosion	Straw, cereals, grass	- fuel leaching - autom. heat exchanger cleaning - coating of boiler tubes - appropriate material selection
	<0.1	HCl emissions	Straw, cereals, grass	- dry sorption - scrubbers - fuel leaching
	< 0.3	Dioxin, Furan emissions	Straw, cereals, grass	- sorption with act. carbon - catalytic converters
S	< 0.1	Corrosion	Straw, cereals, grass	See Cl
	< 0.2	SO_x emissions	Grass, hay	See HCl emissions
Ca	15 – 35 % of ash	Ash melting point	Straw, cereals, grass	Temperature control on the grate and in the furnace
K	< 7.0 % of ash	Ash melting point, depositions, corrosion	Straw, cereals, grass	Against corrosion: see Cl
	--	Formation of aerosols	Straw, cereals, grass	Efficient dust precipitation, fuel leaching
Zn	< 0.08 % of ash	Ash recycling	Bark, wood chips, sawdust	Fractioned heavy metal separation
	--	Particulate emissions	Bark, wood chips, sawdust	Efficient dust precipitation, treatment of condensates
Cd	< 0.0005 % of ash	Ash recycling	Bark, wood chips, sawdust	See Zn

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[11] Obernberger, I. Biomass and Bioenergy, Decentralised Biomass Combustion: State of the Art and Future Development, Vol. 14, No. 1, 1998, page 33-38.

3.5 Australian experience and capability with biomass fuels

A number of organisations within Australia and New Zealand have demonstrated capability in analysing solid fuels. These include:

- CSIRO
- HRL Limited in Victoria
- Scion in New Zealand
- ALS Laboratory Group
- University of Newcastle
- University of Sydney
- Ultra Systems Technology Pty Ltd, in Queensland

A number of major technology and equipment organisations have also been involved in bioenergy plant design and construction in Australia, primarily in the sugar industry using bagasse as fuel. Companies that offer boiler supply for the industry include:

- RCR Energy Systems
- Visdamax (Malaysia)
- Wärtsilä (Finland)
- Metso (Finland)
- Gasco
- Vyncke (Belgium)
- Fitzroy Engineering (NZ)
- Boustead Maxitherm

These organisations and others all offer particular designs and skills, which are based on their own experience in Australia and overseas and also licensing agreements with other specialist overseas groups.

4. Sustainable biomass supply

4.1 Summary

Plant biomass for energy is available as residues from processing operations such as sawmills and sugar mills. In this case the biomass fuel can often be utilised on-site by the processing facility that generated it to help meet process heat and power demands whilst at the same time avoiding waste disposal costs. Potentially, any surplus power can be sold to the grid and surplus heat sold to nearby users.

Plant biomass is also available as residues from forestry or agricultural operations (such as cereal straw and vine prunings) or as purpose-grown crops. In many situations more than fifty percent of the cost of producing energy from such crops can be attributed to the costs of producing, harvesting, transporting, processing and conditioning the biomass feedstock. The very low bulk density of most biomass feedstocks prescribes that volume, rather than weight, invariably limits the transport of wet or dry biomass. A wide range of options exists for the various components of a biomass supply chain and selection of one component (such as the type of harvester) often impacts on the other components. The selection and logistics of the biomass supply chain can be critical to the viability of a biomass energy project.

This chapter focuses mainly on biomass feedstocks from cereal crops, plantation forest or short-cycle crops rather than from agricultural, municipal or industrial organic wastes. Most countries and districts have access to one form or another of biomass supply and often in relatively large quantities. Even if classed as a “waste” product, the resource should be assessed as to its sustainable supply over the long term. Biomass feedstocks available as co-products from farms, forests, processing plants and municipal treatment plants are normally limited in the total volume available depending on population, size and scale of the source. Where additional biomass is required to ensure a sufficient supply of fuel exists for a bioenergy conversion plant over the long term, then increased efficiency of conversion processes, multi-feedstock supplies or possibly the more costly option of growing energy crops can be considered.

For specific biomass feedstocks to provide vegetable oils for biodiesel or sugar/starch for bioethanol, energy crops will also need to be grown. In either case competition for land use, nutrients and water resources then needs evaluation. Where biomass transport and trading are involved, methods to measure and certify the resource are required to ensure that the quality is maintained and the risk of spread of pests and diseases is minimised.

Combustion systems tend to be more tolerant of biomass fuel quality (moisture, piece size, etc) than other technologies such as gasification. Matching the fuel characteristics to the design of energy conversion plant is critical for efficient system performance including operating costs and emissions.

4.2 Introduction

Converting biomass resources into useful forms of bioenergy using a wide variety of processes is well advanced and many examples of mature technologies exist in Australia as well as overseas[1]. Often the major challenge for a project developer is not selecting the conversion technology, but to deliver the biomass feedstock to the conversion plant gate in a form that consistently meets an agreed set of quality standards and characteristics and is at the lowest cost in terms of $/GJ delivered. This chapter discusses the closely inter-related aspects of feed quality, harvest, transport, process and delivery.

In many situations, up to fifty percent or more of the cost of producing bioenergy can be attributed to the cost of producing, harvesting, transporting, processing and conditioning the biomass feedstock. This “biomass supply chain” is critical to the viability of any biomass energy project, and is therefore covered in some detail in this report. In many respects the Australian biomass industry is still in its

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1 Sims R E H (2001).The Brilliance of Biomass – in business and in practice. James and James (London), 316 pages.

infancy and lacks practical demonstrations; so overseas practices and experiences are examined to provide information for the emerging local industry. Exceptions include cereal straw and sugar cane harvesting which in essence, are similar to biomass supply chain systems.

A wide range of options exists for each separate component of the harvesting and handling chain. These vary with the nature of the biomass, whether it is animal slurry, straw, wood chips, forest arisings (residual branches, reject logs and tops), or whole trees. In all cases the objectives should be to minimise energy inputs, handling, and storage losses but to maximise the payloads on transport vehicles.

Many equipment combinations are feasible when developing a given biomass supply system, and the interactions between each component of the system can be complex. Selection of one particular component can restrict the choice of other components further along the chain to form a workable system. For example if a cut and chip harvester is used for short-cycle crops, natural drying of the chips during long term storage in large piles is not practically feasible since rapid physical deterioration of the wet chips would result. In such cases harvesting and storage of whole trees or branches (Figure 4-1) with chipping immediately prior to delivery to the conversion plant can be a preferred option, but may carry additional costs for having to set down then pick up the material again.

Figure 4-1 **Whole eucalyptus trees harvested at 3 years old and stored ready for processing**

4.3 Sustainable supplies

When developing a bioenergy project to provide heat, power or biofuels, the biomass resource is a key issue to be resolved. Long term, secure supplies of sustainably produced biomass are ideal but not always easy to achieve. This section is based on an IEA paper[2] “Bioenergy Project Development and Biomass Supply – Good Practice Guidelines” (also written by the author of this chapter, and available as a free download).

4.3.1 Assessing the biomass resource

There is a need for policy makers to better understand the biomass resource base, its measurement, the potential competition for its use for non-energy purposes, constraints from land use and water uptake, nutrient recycling and replacement, and the benefits and disadvantages from the utilisation of biomass on a sustainable basis. Some forms of biomass such as wood process residues have been utilised as a combustion fuel for decades. Residues from agriculture, plantation forests and food and fibre processing operations are collected worldwide and used in a wide variety of bioenergy

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[2] IEA, (2007). Bioenergy project development and biomass supply – good practice guidelines. International Energy Agency OECD/IEA, Paris. 66 pages. http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=1933

conversion plants. These are difficult to quantify. Others such as specialist energy crops including *Miscanthus*, *Jatropha*, short rotation *Salix* (Figure 4-2) and *Eucalyptus* etc. are new and there is still much to learn about their production, harvesting, storage and processing.

Figure 4-2 Harvested Salix (willow) stems awaiting collection with recent coppice re-growth evident in the foreground and 2-year rotation biomass in the background.

Obtaining accurate data on the biomass resource available even in a local district can be challenging as it varies from year to year and across seasons. A very useful publication, the *Biomass Assessment Handbook*[3] helps provide the tools needed to understand the biomass resource base and its assessment, whether it be for woody biomass, herbaceous biomass, or crop residues. Measuring tree volumes, assessing the moisture content of a truck load of wood chips, calculating the energy content of a field of straw, using remote sensing techniques to measure variations in crop yields in a district, are just a few examples of the challenging tasks needed for accurate biomass resource assessment.

Where sufficient data is available, GIS (geographical information systems) and overlay mapping techniques can be used to identify known biomass resources or to match proposed energy crops with current land use, soil types, rainfall and sunshine hours. This can also be a powerful tool to identify the best location/s for a proposed bioenergy plant, depending on the volume of biomass needed per year, the nature of the roads for transport, and access to existing power lines. Where the international export of large volumes of biomass is anticipated, good rail or road access or close proximity of the plant to a port is essential.

4.3.2 Moisture content, dry matter content and heating values

The interactions between moisture contents, dry matter losses in storage over time, heating values and biomass bulk densities need to be understood as they affect the overall costs of transport, storage and conversion of the biomass (Figure 5-1). Most forms of biomass contain water to varying degrees and this affects the energy content of the material. Measuring the moisture content is critical for solid biomass assessment and also when purchasing it to determine a fair value. It can be achieved by taking samples (Figure 4-4), weighing them, oven drying at around 90°C until constant weight, then reweighing the remaining dry matter to calculate the moisture that has been driven off. Using electronic instruments such as conductivity probes pushed into a pile of straw or wood chips is more rapid – though their accuracy can vary.

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[3] Rosillo-Calle F, Hemstock S, de Groot P and Woods J, (2008). Biomass Assessment Handbook, Earthscan, 296 pp ISBN 9781844075263

Figure 4-3 Sampling each load of biomass on delivery for various parameters

Sampling, including moisture content, is standard procedure at large biomass plants to ensure quality factors are maintained and a fair means of payment to the supplier can be assessed rather than be based on tare weight alone.

Evaluating the available biomass resource for a region, or indeed for a single bioenergy heat, power or biofuel plant, must account for the moisture content which can vary considerably and hence complicate the assessment. The atmospheric ambient conditions, (mainly temperature, air movement and humidity), together with the structure of the tissues of the specific biomass, determine the natural release of moisture from the biomass by transpiration and evaporation, and hence the drying rate. A branch or tree with leaves left on after felling results in faster transpirational drying taking place by bringing down the moisture content level than for stemwood alone.

The moisture contents of slurries and wet biomass feedstocks, as used with anaerobic digestion or fermentation plants, are less important than for solid biomass since the feedstock is usually not transported long distances and will not deteriorate. However, the total solids content of a liquid feedstock can have an effect on the performance efficiency of a biogas plant and, if dilute, the cost of storing larger volumes in tanks. Also the moisture content may need to be determined if the green crop, slurry or effluent is traded.

4.3.3 Long-term biomass supply

Using biomass from the by-products of a crop or process (often classified as “waste”) makes good economic sense. However there is a limit to the amount available depending on the area of the crop grown for its primary product or the amount of waste produced from a food or fibre processing operation. Many businesses are attempting to minimise their wastes by either improving the process or utilising the material for co-products other than energy. So over time the volumes of a “waste” biomass resource available for energy purposes could decline.

Increasing the available supply of biomass in future could therefore depend to a greater degree on the active production of energy crops on surplus arable land (as in Europe and the USA), marginal and degraded lands, or plantation forests. However purpose-grown energy crops are unlikely to become economic within the next decade in Australia without development support and unless they can produce multi-products or demonstrate valued co-benefits such as improved balance of trade or reduced future fuel supply risk.

Another co-benefit is that, with careful management, improved quality of degraded soils can result. For example, in Australia, large areas of agricultural land that are susceptible to salinity (now resulting from historic tree clearing) may be protected in part by growing belts of mallee eucalypts to manage salinisation by lowering the water table across cereal growing land (Figure 4-4 and Chapter 9). Also where energy forests or crops are grown as riparian strips, then the quality of nearby waterways and lakes can be improved by reducing the nutrient loadings from the run-off of animal wastes or from excessive application of fertilisers. On the other hand, if crops are poorly managed, then increased biomass production can lead to losses of terrestrial carbon and the degradation of biological diversity.

Figure 4-4 Eucalyptus oil mallee trees grown in belts

Bioenergy conversion facilities may be considered where there is uncertainty over biomass supplies because the low value biomass feedstock currently available could become feedstocks for competing uses in the future. Potential investors in bioenergy facilities will be cautious about projects with a lifecycle of 15-20 years where there is uncertain biomass availability at no fixed prices, and hence considerable exposure to market risks. Therefore negotiating long-term contracts with the biomass suppliers to maintain security of supply, as well as to improve biomass quality, is highly recommended to reduce these risks.

4.4 Production and use of sustainable biomass

A significant barrier to the use of biomass in some regions is the public concern that its production is non-sustainable. Under some circumstances, such as if harvesting native forests at a rate greater than their rate of natural regeneration, this view is clearly correct. There are simply some sources of biomass that, for a variety of reasons (such as their aesthetic, recreational, biodiversity, water cycle management or carbon stock qualities), should never be used for energy purposes. However for other biomass sources this is not always so clear cut. The debate continues on what exactly is the definition of 'sustainable biomass'. Certification schemes, criteria, indicators and guidelines for biomass defined as being sustainably produced are under discussion[4].

Residues from plantation forests that would otherwise be burnt in the field or left to decay, and wood process residues that would otherwise be disposed of in landfills, can normally be classified as sustainable forms of biomass. Growing sugarcane for ethanol production and using the bagasse for heat and power generation possibly is sustainable as long as the soil nutrients are well managed and any nutrients removed at harvest are eventually replaced. However the intensive production of corn or cereals for ethanol production, or oilseed rape for biodiesel production, needing relatively high inputs of fossil fuels, nitrogenous fertilisers and agri-chemicals, possibly are not, depending on the definition of "sustainability". The Global Bioenergy Partnership[5] is investigating this in association with the IEA Bioenergy Implementing Agreement[6]. The industry and regulators need to clarify this issue since public concerns about the environmental impacts of using biomass as an energy source lead to a number of frequently asked questions.

- Will the use of land for energy cropping reduce the area of land now used for food and fibre production so that scarcities will result?
- Will genetically engineered trees and crops need to be developed specifically for use for biomass energy supplies?

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[4] See for example www.pefc.at; www.globalbioenergy.org; www.ieabioenergy.com.
[5] Established by the G8 meeting at Gleneagles in 2005 – see www.globalbioenergy.org
[6] Task 40 Sustainable Bioenergy Markets, Trade and Resources – see www.bioenergytrade.org.

- Will soil nutrient levels be depleted by continually removing large quantities of biomass material such as crop residues from the land to supply nearby conversion plants?
- Will biodiversity be further threatened and agri-chemical use increase if ever-greater areas of monocultural crops are grown?
- Will planting large areas with fast growing trees as energy forests reduce both water run-off and percolation into the groundwater, thereby affecting downstream users?
- Will transport of large quantities of biomass to the power plants result in increased traffic congestion, noise, dust, road damage etc?
- Will an increasing number of wood-fired heat and power plants lead to an incentive for investors and shareholders to support the cutting down of existing forests?
- Will stack emissions from municipal solid waste-to-energy plants, and also possibly from wood-fired biomass plants, contain toxic substances such as dioxins?
- Will using waste for energy purposes reduce the desirable incentives to minimise and recycle waste materials if it is cheaper to burn it?
- Can biomass be produced in a truly sustainable manner as well as being renewable?

4.4.1 Source of residues and wastes

Organic residues and wastes from other primary industry activities are often cost effective feedstocks for bioenergy plants. As a result many of today’s commercial bioenergy plants around the world have resulted from niche market opportunities within forestry, food production, food processing, and other primary industry sectors where on-site biomass “waste” feedstocks are available that may otherwise require costly treatment or disposal. Where biomass residues (such as corn cobs, tree bark, or animal fat) have already been delivered to a processing site along with the primary product (such as corn kernels, pulp logs or meat), the biomass value ($/GJ) is usually very competitive, particularly where there may even be an avoided disposal cost. For example the lignin content of black liquor (the residual material from the wood pulping process) is commonly used as a feedstock for heat generation in pulp mills; animal wastes suitable for biogas production are used on farms; and dry wastes such as sawdust, rice husks and palm oil kernels are combusted on-site in boilers to provide cheap process heat for the factories. Bagasse, the fibre residues from sugarcane processing, is another important feedstock for heat and power cogeneration that is already widely used in Australia and overseas.

Other biomass materials normally left in the field at harvest, such as cereal straw, forest arisings (tree branches and tops) and sugarcane trash, can be collected and stored as fuels for heat and power plants. This is less common, as the additional costs for collection, transport and storage increases the total delivered cost of the biomass (in terms of $/GJ) to any bioenergy facility.

4.4.2 Woody weeds

Where non-native trees have established naturally, such as gorse in New Zealand or mimosa in Northern Australia, then some land clearing is encouraged to control the spread of the species. The biomass collected could then become a useful fuel. A limitation, however, is that long-term supplies of the resource cannot be guaranteed should complete eradication prove successful after maybe 5 or 10 years. By this time, the land will have begun to revert to its former native vegetation and no more biomass supply would be available. Therefore a bioenergy plant using the feedstock would become short of fuel. Dependence on a single feedstock is often risky and encourages plant designs to handle multi-feedstocks , although these plants can be more difficult to design and potentially more costly.

4.4.3 Land use change for energy crops – competition with food and fibre

Land requirements for future energy crop and energy forest plantations may compete with land currently used for production of food and fibre products. Land use change will only happen on a large scale if the landowners can gain more revenue or other benefits, such as by growing a new energy crop that may offer greater revenues than those received from growing traditional crops. The difficulty is that traditional forms of energy remain relatively cheap, so energy crops have to compete with these low $/GJ prices. Conversely to grow an energy crop requires input of seed, fertiliser, chemicals, machinery, fuel, labour etc. and hence requires a good sale price to compete with the revenue from growing other crops. In essence, biomass already collected at a site (such as bark at a pulp mill) is cheaper than collecting more dispersed biomass residues (such as forest residues), which in turn is cheaper than growing purpose-grown energy forests.

Therefore to make energy cropping a viable business proposition for a landowner, either agricultural subsidies need to be introduced or adjusted to encourage energy crop production along with food and fibre crop production, or the co-benefits from growing the energy crop need to be better valued. These can include landscape enhancement, wild life habitat, improved water quality, rural development, employment opportunities, carbon sequestration, etc. Planting a mix of species is sometimes worth considering, not only for landscape benefits but also for added resistance to the spread of pests and diseases. New crops can have a major visual impact such as when oilseed rape was first introduced into the UK since it has a bright yellow flower. Whether the impact on the landscape is seen to be beneficial or negative depends on where the crop is grown, perception by local individuals, the character of the existing landscape, and how intensive the crop might become within a concentrated area. Developers and growers could undertake a landscape assessment process in order to better understand and communicate the expected impacts on the landscape.

The area of land needed to grow energy crops will ultimately depend on the annual yields of biomass as achievable on a sustainable basis, the water requirements and availability, adequate recognition of co-benefits, government support schemes, and the conversion efficiency of the resource to useable energy carriers. As an example 240 ha of energy forest plantation yielding 15 oven dry tonnes (odt) /ha/y of woody biomass would be needed per MW_e of installed capacity to supply a wood-fired power plant, assuming 35% efficiency conversion of biomass to electricity when running for 7,000 hours per year. For a CHP plant of say 70% efficiency when much of the heat is utilised, less of the solar energy stored in the biomass would be wasted as useless heat.

Careful site selection may also reduce the need for control of pests, as well as weed and disease control by agri-chemicals.

4.4.4 Sustainable land use

Harvesting of biomass on a non-sustainable basis for bioenergy purposes, or indeed to produce other products, or clearing native forests to provide more agricultural land, are considered unacceptable to most people. Land clearing is continuing in several world regions but usually standing or cut forests are burned in the field with no consideration to use the biomass for energy. The loss of carbon stock and resulting increase in atmospheric carbon content are serious concerns, as is the loss of biodiversity[7].

When land use change occurs in order to grow any new crop, the type and proximity of habitats adjacent to it will need consideration, as will resulting indirect land use change[8]. Some crops may attract bird life to feed on the insects or seeds, some may compete for water with neighbouring wetlands, and some may produce self-set wilding plants in nearby fields that will require future eradication.

The intrinsic ecological and historic value of a site should also be assessed prior to any activity related to biomass production occurring, whether for energy or for other purposes. Many countries have clear regulations regarding protection of sites of special historic or scientific interests or identified as conservation reserves. Not all archaeological sites appear on maps as they have not been properly surveyed or recorded, and in some instances are known of only by oral history from the indigenous people. Legal consequences may result from protected habitat or wetland destruction and advice from the local authorities should be sought at an early stage of the process.

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[7] It should be remembered that much of today's agricultural land was once under native forest in many OECD countries. In Australia, USA and New Zealand for example, land clearing practices have continued until fairly recently.

[8] Fritsche U R, Sims R E H and Monti A (2010) Direct and indirect land use competition issues for energy crops and their sustainable production – an overview Special Issue "Biofuels: reconciling environmental and economic concerns" Biofuels, Bioproducts and Biorefineries. DOI: 10.1002/bbb.258 http://onlinelibrary.wiley.com/doi/10.1002/bbb.258/abstract

4.4.5 Nutrients and cycling

When any agricultural product is removed from the land some nutrients are extracted with it. This is the case whether the product is milk, wool, meat, cereals, fruit, sugar or wood. Continuous large-scale production and harvest of forest plantations and energy crops could reduce soil fertility levels, lead to leaching of nutrients and increased use of agri-chemicals. A nutrient mass balance can be undertaken to assess the quantities of nutrients removed on an annual basis. Carbon, hydrogen and oxygen are replaced naturally during photosynthesis from water and carbon dioxide, and since it is only the hydrocarbons needed for combustion, then in theory all other elements could be captured and recycled. Where only woody biomass is removed from a forest, there is less nutrient loss than if the leaves, tops, small branches and bark are also utilised

Attempts have been made to return certain soil minerals, such as phosphates, back to the forest via the recycling of the wood ash from biomass burners. In most cases however this is not feasible and any minerals taken from the soil during crop growth and harvest may need replacing. Regular soil tests enable levels of key minerals to be monitored and, where necessary, for artificial fertilisers, compost or animal manures to be applied to replace them. In this regard, energy cropping is no different to traditional agriculture.

Energy cropping has been linked with the land treatment of sewage and industrial sludges and effluents. The nutrients can then be recycled and any possible health concerns from viral and bacterial infections are avoided as the crop is not part of the food chain, although in some countries there are stringent regulations concerning the land treatment of bio-wastes. However the storage and irrigation costs tend to be prohibitive compared with other forms of sewage or effluent treatment and often only limited volumes are available from sources close enough to cropping land. So it has not become common practice in Australia.

In the longer term, genetically modified crops grown specifically for energy purposes may become feasible and accepted – perhaps more so for energy crops than for food crops. These could be leguminous and avoid the need for nitrogenous fertiliser applications. With careful management, recycling of other nutrients may become feasible, as in the manner of today’s organic food farms.

4.4.6 Water management

Some energy crops take up more soil moisture by transpiration than others. For any crop, a grower should consider the implications of water demand and rainfall when choosing a species and variety, not only on the biomass yield but also, if to be planted extensively, on any downstream water users. In some regions plantation forests have been associated with reducing the volume of groundwater available due to higher levels of evapo-transpiration compared with other crops or native vegetation. In contrast to this, the use of mallee eucalypts on farms in the Australian wheatbelt can effectively utilise excess water that may otherwise cause salinity problems. A perennial plantation can be designed to minimise negative impacts of water use and develop benefits by such factors as planting in one large block or several smaller blocks, planting blocks sequentially over the years to produce a range of ages for harvesting in sequence, or avoiding planting near bore holes unless the aim is to reduce water contamination.

Crops more suited to arid or dryland regions tend to put their roots down further, which can have an impact on soil nutrient levels. Conversely fast-growing tree crops in moist soil can form a dense mat of roots down to a metre or so which enables them to become an effective mechanism for soaking up nutrients and act as a buffer. A possible problem may be the damage by vigorous rooting systems to any field drainage system in place. Another benefit may be that access to machinery, including for harvest during wet seasons, which can be facilitated by the root mat providing support for the vehicle weight.

4.5 Increasing local biomass production

4.5.1 Improving crop management and yields

Soil types best suited to growing energy crops can be identified and shallow or dry soils avoided as yields are likely to be low and nutrient reserves limiting. Some dryland crops such as *Jatropha* or

Euphorbia could be suitable for arid conditions but for any plants experiencing water and nutrient constraints, yields per hectare are likely to be relatively low, thereby requiring greater harvesting and collection costs.

Irrigation is an option for growing an energy crop in dry regions to optimise yields. However the cost of the irrigating equipment may be prohibitive, water may be limited and/or costly, high labour inputs are often needed, and the additional yields obtained do not always warrant the extra costs involved.

It is often preferable that biomass supplies are available for harvest on a year-round basis. For crops that are harvested in the winter, clay soils are particularly prone to structural damage from heavy machinery when wet. Over time this can reduce the yield potential. Crops requiring annual harvesting are therefore not well suited to floodlands, boggy areas or sensitive wetland sites. This problem can be avoided in some European countries because the soil freezes in winter.

4.5.2 Integrated harvesting

There are usually fixed amounts of available biomass in any given district, based on existing agricultural, forestry, municipal and industrial activities. Where some of the biomass is currently being left on the ground after harvest of the crop, then greater efforts to collect it may be feasible. However a separate recovery process would probably be for a relatively high cost, and integrating the harvesting of this biomass with the harvesting of the primary product could be warranted. Skidding whole trees after felling to a central processing site nearby in the forest is an example. The logs are separated from the arisings (the remaining biomass material), thereby giving two product streams that can then be transported separately to sites for further processing. Increased nutrient removal can be a constraint to taking residues and arisings from some lower fertile soil types, unless nutrient cycling is achieved.

4.5.3 Breeding of new crop varieties

Most traditional food and fibre crops have been bred for decades to increase their yield and the quality of the product. For example, wheat now commonly produces 10 tonne of grain per hectare in some countries whereas this was rare only 20 years ago. The variety grown also affects the quality of the bread produced. Similarly oilseed rape (canola) crops have been bred to enhance the yield and quality of the oil for cooking, though high erucic acid varieties have also been developed for their special properties as an industrial lubricant.

Breeding of crops to maximise their energy content is rare, although varieties of *Salix* (willow), coppiced every 2 – 5 years for biomass, have been selected in order to reduce rust infestations that lower yields in the UK. Overall however, the breeding and selection of crops grown mainly for energy use is at an early stage of development. In the future it could be that genetically modified energy crops could be produced that will be more efficient as “solar energy collectors” (akin to the present C4 plants such as sugarcane and sorghum). Therefore GM crops for biomass could possibly be higher yielding but also require lower inputs of fertilisers, have greater resistance to pest and disease, and be dryland tolerant. If such an ideal new crop is ever produced, the potential for producing biomass as an energy source could increase significantly.

4.5.4 Growing energy crops

Another way to produce more biomass is to grow it as specialist energy crops. These may be vegetative, perennial grasses cut annually or even 2 or 3 times each year, short rotation plantations harvested every 3 to 10 years and either replanted or allowed to regrow from the cut stump (coppicing), or annual crops purpose grown for their energy components such as oil, sugar or straw.

The three major elements that need to be considered when growing energy crops are:

1. Assessing whether the selected crop will be economically viable to grow, harvest and store under the specific circumstances of the market at that time.

2. Selecting the most appropriate species and provenance to best match the soil types and climatic conditions.

3. Crop management - to maximise environmental benefits, minimise any negative impacts and to fit in with conventional crop rotations and machine and labour availability.

A grower will select a suitable site for producing an energy crop once a reliable market has been identified and the economic viability confirmed. Site selection will depend on such factors as landscape, visibility, road access, proximity to a bioenergy processing plant, soil type, water availability, disease and pest history, archaeological history, competition for growing other crops and public access. Where a popular view is likely to be blocked or modified, or access to a public right of way reduced, then public resistance to the project will be increased.

Landscapes of specific quality and with conservation values may be under special protection and local policies may apply that inhibit new crop production. Tree crops can also affect visibility of paths and views and impact on people's visual amenity. Straight rows and boundaries for tree plantations, for example, can have a greater visual impact than planting around the contours. Conversely some plantations may contribute positively to variations in landscape and biodiversity, provide shelter and wind breaks and provide recreational value.

Where a heat demand exists on a farm or for a local industry, it could make sense to use straw or other crop residues from existing crops. Where no other suitable biomass resource is available, a crop could be grown to meet that purpose. The sale of any surplus biomass by a landowner could generate additional income if there is a market, and also make better use of any under-utilised land.

For all biomass producers, if there is a bioenergy plant within an economic transport distance, the energy crop producer would need to consider how best to become part of the supply chain. This may involve agreeing to a long-term supply contract with transport charges placed on the grower. Therefore the supply radius might be limited to around 50 km. Forming a co-operative between several growers may assist bulk selling to the bioenergy plant owner, as is common with vegetable and other horticultural products. Alternatively a group of growers could create a local market by collaborating on their own bioenergy plant development. Grants and other subsidy payments may be payable in some regions to assist with such a development.

4.6 Biomass quality standards and fuel specifications

Biomass feedstocks, being of biological origin, are often bulky, have a high moisture content, and of variable and unpredictable quality. For simple combustion systems some variations in the feedstocks are of little consequence within reasonable bounds. However other conversion equipment (such as gasifiers connected to gas engines and other internal combustion engines) need the biomass to be within stringent specifications if they are to be operated satisfactorily and if manufacturers' warranties are to be maintained. Feedstock standards are therefore needed to maintain quality within clearly defined specifications.

Techniques for biomass upgrading by natural drying, pelletising, briquetting etc. are advancing. For biodiesel, a European standard is in place and other regions are developing theirs. An international bioethanol fuel standard is also being contemplated by the IEA, Advanced Motor Fuel implementing agreement[9]. Fuel consistency may be achieved more easily using the biomass produced from dedicated energy crops than using that produced from a variety of sources such as wood process residues from different sawmills and tree species. Similarly, vegetable oils vary with the oil crop species and also possibly daily where used cooking oils from restaurants are collected.

Most bioenergy plants are designed to suit a specific biomass feedstock, but it is likely that the mixture of biomass available, and its specific characteristics, will change over time. This affects the design of the bioenergy plant and can even shorten its economic life due to obsolescence if suitable biomass feeds become unavailable.

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[9] http://www.iea-amf.vtt.fi/

4.6.1 Method of payment for the biomass resource

A fair means of payment is needed to ensure the biomass producer receives a proper return for supplying good quality and consistent feedstock, because biomass can vary from truck load to truck load in terms of its dry matter content, energy value, soil contaminants, foreign bodies such as stones or metal parts from the harvester, and source of origin.

It is not sufficient simply to weigh a truck on arrival at a bioenergy plant to assess the weight of biomass and make a payment on that basis. As for a cereal crop, the moisture content will vary from load to load and paying for water is not acceptable. Sampling the biomass material on the truck, analysing it for moisture and other parameters depending on the bioenergy application, making payment on this basis (with penalty deductions or even rejection of the load for very high moisture, contamination by soil, rocks etc.) are options that will need contractual agreements between the bioenergy plant owners and the landowners and biomass suppliers.

4.6.2 Disease carriers

Untreated biomass material such as the bark component of wood chips, seed contamination of straw residues, or soil contamination of vegetative grass energy crops, can carry a wide range of pathogens and weed seeds. Transporting biomass materials between locations can cause the spread of diseases, pests and weed proliferation for which some form of management may be necessary. Additional concerns arise where biomass, in the form of sewage sludge, animal manures, or effluent from meat and other food processing industries, is utilised either for direct combustion, as an energy feedstock for biogas plants, or indirectly if applied to an energy crop as a form of treatment. Biomass processed into other energy carriers such as pellets, bio-oil, liquid fuels etc. prior to transport off-site, and especially for export, can normally overcome any contamination risk, especially where heat is involved in the process.

Certification of the resource and a complete tracking of its origin and history are technically feasible (although they do add to the final cost of the biomass). This would serve to overcome any concerns that local residents might have about the spread of pests. It would also allay any fears the biomass purchaser and user might have about maintaining acceptable resource quality to suit the bioenergy plant’s handling and processing systems.

5. Supply chain components

5.1 Summary

To produce an efficient biomass harvesting, processing, handling and transport system, selection of individual machinery components and matching their productivity potential is critical if supply chain delivery costs of the biomass to the bioenergy plant are to be minimised.

- ***Harvester machine size and design***
  The ideal harvester will be optimised with regard to many different variables, including: the layout of fields and plantations, spacing between crop rows, available turning circle for machinery, harvesting pattern, terrain, row lengths and hence material harvested per row, suitability for use under wet soil conditions, permitted weight to avoid soil compaction, targeted fuel capacity and consumption, and capital cost. Options to be considered include tractor-trailed or self-propelled machines, side-cutting or central fixed-cutting heads, as well as the physical size and weight to match the type of terrain where the machinery will operate.
- ***Harvester capacity and productivity***
  The harvesting rate (hectares or tonnes per hour), and hence duration of harvesting for a given land area depend on number of machines, requirements for support and transport vehicles, economics of machine ownership versus use of contractors, overall harvesting system costs, and ability to harvest under various terrain and weather conditions. Ideally the harvester design and capacity should permit uninterrupted harvesting and without having to stop to unload the cut material.
- ***Width of cut***
  The machine cutting width has a direct relationship with productivity and the number of passes made across a field. For short-rotation (short cycle) coppiced biomass crops, the cutting head may need to cope with single stem and/or multi-stem trees.
- ***Cutting mechanism***
  Options include single and double disc cutters, chainsaw type cutters, reciprocating knives, hydraulic or belt drive mechanisms. The design of the cutting heads determines the forward harvesting speed, stem diameters that can be cut, width between rows, and possible long-term damage to the soil, perennial crops or coppice stumps. Susceptibility to damage from stones and soil, and blade resharpening are issues to consider.
- ***Comminution***
  Reducing the size of individual biomass pieces for easier handling and transport affects subsequent drying rates, bulk density and hence storage and transport costs. Options for comminution, applied at in-field operations, at forest landings, or at the bioenergy plant, include chipping, hogging, billeting and shredding. If biomass is to be stored in chip form its moisture content should not exceed 20 percent, as biological heating, loss of dry matter and mould formation can result. Spontaneous combustion within storage piles, especially for bagasse (sugar cane fibre) and wood chips can be an issue.
- ***Transfer mechanism from harvester***
  The general preference is for a continuous harvest operation without stopping to unload collected biomass. This helps to maximise productive use of the equipment. Support trucks and trailers are often required to continually transfer the biomass from the harvester to enable high productivity rates to be achieved. The type and capacity of the support transport is largely determined by the amount of biomass that can be carried on the harvester before transfer, access to the field, terrain, and soil type and conditions. Options exist for stem and stick harvesters and balers and also for chippers and billeting machines.
- ***Transport from field to storage or use***
  Options for transporting the harvested biomass to the bioenergy plant or to intermediate storage include carrying the cut material on the harvester directly, collection of whole trees, stems, prunings or sticks from the field or headland with a grapple and trailer or tractor-mounted buckrake, collection and baling of small diameter stick or prunings with a pick-up baler, and

subsequent collection of bales with loader trailers. For stems, sticks and bales this can be done on flat bed or forestry trailers, and for chips and billets via a bulk-commodity trailer. Cereal straw is usually compacted and baled then transported as units rather than in loose bulk form. At the bioenergy plant, specialised handling and conveying facilities for whole straw bales can shred the straw just before feeding into a boiler. Whole bale boilers have been developed in Denmark for smaller scale heat applications.

- ***Road transport***
  The type of vehicle used for road transport of the biomass needs to address any planning constraints, such as permitted number of daily vehicle movements, and maximum payload (weight) permitted on the road. Development of the optimum option will need consideration of the transport distance, road widths and classifications, transport regulations, the desired aim to maximise payloads to minimise costs, means of securing loads, and maximum height of loads or length of truck-trailer combinations. Overseas experience shows that square bales around 800 kg each are usually preferred for low density biomass crops although the John Deere "Energy Harvester" has been developed for baling forest arisings as used in Finland[1]. Under other circumstances it has been found that for long distances, transporting chips can be a better option than transporting forest arisings, bales or whole trees, provided long-term storage is not necessary since chips tend to degrade over time.
- ***Storage of bales and chips***
  When storage is required, bales and chips are generally stored uncovered on concrete pads, on bare ground, covered with tarpaulins, or under roofed structures. On occasions the biomass material undercover is only stored for a few days before use, during which time artificial drying can be achieved if necessary. A key requirement for longer term storage of chips is encouraging air movement and maintaining moisture levels below 20 percent (wet basis) to minimise "composting" of the biomass, loss of dry matter, and deterioration.
- ***Drying***
  The heating value of biomass per unit of weight is enhanced by reducing moisture content. Moisture reduction can be achieved through transpirational drying, natural ventilation during in-field storage of billets, bales, stems or sticks, intermittent artificial ventilation during storage, or through heating the material using waste heat from the energy plant or other cheap heat source if available. Computer simulations have shown that drying chips with waste heat can maximise overall energy capacity of the plant.

5.2 Introduction

The individual components of the harvesting and handling chain are closely inter-connected. The key components are listed below. For each, the interactions affecting other components are noted and practical options to design a complete system are provided. The technologies for conversion of the biomass into heat, power or liquid fuels, are examined in detail in other chapters of this report. The key components of a biomass harvesting and supply system are:

- overall harvester machine size and design concept
- harvester capacity and productivity (ha/hour, overall work rates)
- width of cut
- cutting mechanism
- comminution
- transfer mechanism of biomass material from harvester to the next step in the supply chain
- transport from field to storage (intermediate or on-farm)
- road transport to conversion plant
- storage, if required

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[1] http://www.deere.com/en_US/cfd/forestry/deere_forestry/info_center/feature_stories/energy_from_forest.html

- drying, if required.

For some forms of biomass such as vegetative grasses, canola and straw, conventional agricultural machinery is available for harvesting and preliminary processing. Examples include cereal straw balers, forage harvesters converted for use with coppice willow crops and combine harvesters with modified threshing drums and heading equipment. To extract woody biomass from forest plantations, the use of traditional tree harvesting equipment may be technically suitable with the integrated harvesting of the biomass component of the trees along with the stemwood to be used for traditional wood products. Equipment such as feller-bunchers and chipper-forwarders may be suitable for use with short cycle tree crops, depending on the harvest cycle period for the trees and the consequent individual stem size. The number of stems per tree will affect the choice of harvester, with multi-stem trees such as eucalypts posing particular problems for many existing harvesters.

Transport of forest or crop biomass is normally limited by volume more than by weight[2]. The interaction between truck payload, truck volume, and the moisture content of the biomass affects the cost per GJ of energy delivered by the biomass. In Figure 5-1 this is shown for a 36 m^3 truck with a 26 t payload that is weight limited when carrying wet biomass but volume limited for drier loads (upper chart). More energy is carried when the loads are drier. However the cost per tonne carried increases for dry biomass loads (lower chart) but the more important cost per GJ of energy delivered is optimum when the biomass is around 30-40% moisture content, wet basis. Thus road transport over long distances may benefit from drying, compaction or comminution of the biomass to achieve the maximum payload possible.

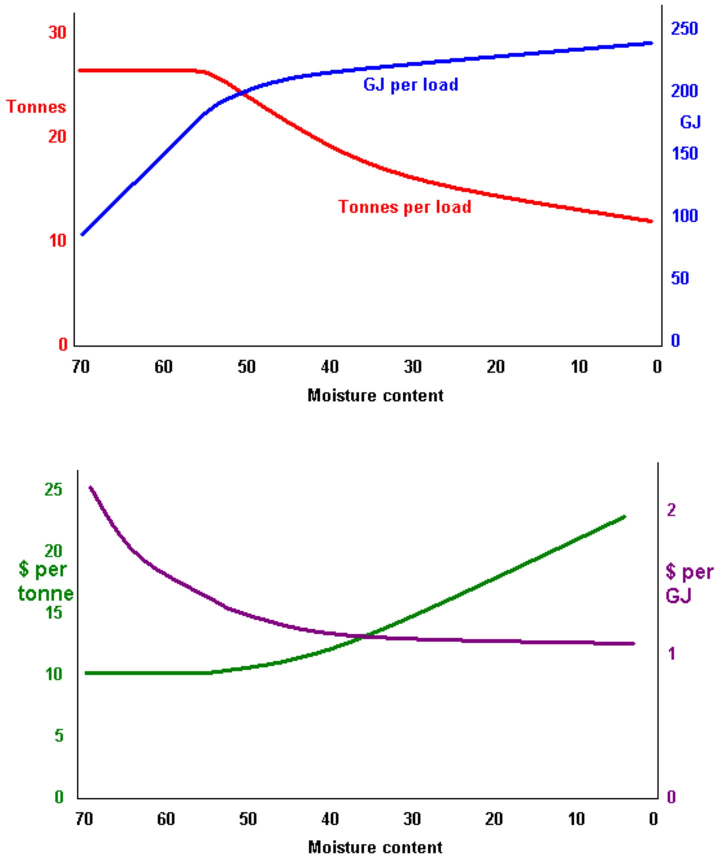

Figure 5-1 **Example of the interaction between biomass moisture content and transport costs**

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[2] Hall P, Gigler J K and Sims R E H. 2001. Delivery systems of forest arisings for energy production in New Zealand. Biomass and Bioenergy 21 (6), 391-399

Large quantities of biomass are already harvested in well-designed systems. For example, the sugar cane industry already has considerable experience of harvesting and handling up to 3Mt/y at any one plant. Where practically feasible, using existing, commercially available equipment (perhaps after modifying it) is often the most viable option. For example oilseed rape used for producing biodiesel is harvested using conventional cereal combine harvesters. Vegetative grasses to be used for combustion feedstock can be cut with conventional crop mowers or windrowers, and then baled using conventional hay balers. The balers could then be used for making silage bales in spring, hay bales in summer, straw bales in autumn, and energy crop bales in winter. This would give all year round work to the owner-contractor, and therefore spread the fixed costs over a greater number of bales per year, thus minimising the costs per bale. Where no commercial equipment is available, or there is limited opportunity for reducing costs of existing systems via technical innovation, the need to develop specialist harvesting and handling equipment can arise. Many prototype machines have been developed around the world but few have proved successful enough to reach the commercial manufacturing stage. There is often a perception of risk associated with such development due to the unknown market for such machines. This, along with the significant up-front costs of a thorough RD&D development program, can stifle attempts to improve supply costs through innovative new equipment.

Harvesting operations, transport methods, and the distance to carry biomass feedstock to the conversion plant, also impact on the energy “balance” of the overall biomass system. That is, any fossil fuels utilised in the biomass supply chain will detract from the greenhouse gas mitigation benefits achieved by the production of renewable electricity or transport fuels when the biomass is processed. The heat or power generating plant, or a multi-product biorefinery, should be located on a site where transport costs are minimised since the biomass usually has a low energy density and hence is costly to transport. However, although feedstock transport must be considered carefully, experience and analysis also shows that economies of scale possible from the construction of larger biomass-fired plants are often more significant than the additional transport costs involved to provide the fuel for such plants[3].

Machine size and design affect the following parts of the biomass production and harvesting system.

- Establishment and layout of fields or forests, to leave optimal access for manoeuvring of machinery
- Space between the rows and turning circle space at the headlands for either making three point or U-turns to enable the machine to return down the adjacent path to that just traversed
- Harvesting pattern; for example travelling up one row and returning down the next, working inwards from around the perimeter, or working across the area in “lands”. (Lands were first developed for ploughing with horses to minimise the distance walked with the plough out of the ground)
- The optimum row length depends on the rate of filling the support truck or trailer travelling alongside the harvester or the capacity to carry cut material on the harvester
- Longer rows give greater field efficiencies
- Weight of machinery and footprint area of tyres or tracks and hence effects on soil compaction and traction (Figure 5-2).
- Fuel consumption
- Capital cost investment, which is usually high and therefore requires high annual hours of productive use to reduce the fixed machine costs per tonne or per hectare harvested.

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[3] Dornburg, V. and Faaij, A., 2000. System analysis of biomass energy system efficiencies and economics in relation to scale. Proc. 1st World Conference and Exhibition on Biomass for Energy and Industry. Sevilla. CARMEN

Figure 5-2 Self-propelled Swedish prototype harvester

Machine options to be considered at the early design stage are based on some or all of the following principles.

- Trailed machine - smaller and lighter, or a self-propelled machine -larger and heavier.
- Left / right-sided cutting head or a central head fixed across the front of the machine.
- Size and number of wheels and tyre sizes and types to carry the weight or the use of tracks or ½ tracks to reduce soil structure damage and compaction in wet conditions.
- Carrying the cut material on board until deposited at the headlands for later collection; or the transfer of material as it is cut to the support vehicles/trailers running alongside; or dropping the cut material directly on to the ground for later collection.

The physical size of a harvester, which is limited by:

- tractor power available if trailed or, the engine size to be installed if self-propelled
- the soil type and expected moisture content range at harvest time, wet clay soils providing poor traction and a high risk of soil compaction, reduced regrowth and root damage
- the nature of the terrain, a low centre of gravity being needed on steeper land
- whether there is room available to manoeuvre at the ends of the crop or tree rows
- the ability to operate in small fields or to be transported down narrow rural roads.

5.2.1 Harvester capacity and productivity

Machine capacity and productivity (ha/hour, overall work rates) affect:

- the area to be harvested in a season by one machine, which determines whether owning and operating it is an economic proposition or not as the fixed costs are spread further
- the number of machines needed for the total area to be harvested with minimum risk of crop losses due to adverse weather conditions within a limited harvesting period
- the number of support vehicles needed to collect and transport the cut material from the field
- the total harvesting costs, including labour, usually expressed in terms of $/tonne or $/GJ harvested.

The size and design of the harvester is limited by:

- the period available for harvesting to take place

- the soil type and terrain, affecting forward speed, traction and stability
- the typical yield, physical piece size and layout of the crop to be harvested
- the row width and dimensions of the field or plantation
- the machine cutting width
- the ease of transporting the machine by road between jobs
- the need to obtain access and to work around other crops in the same area
- the forward speed possible during harvest and when travelling on the road.

Options available to the grower or harvesting contractor are to:

- cut only when the soil is firm, and not when wet periods hinder access
- cut regardless of whether the soil is wet or dry
- cut all year round if agronomically sound to do so, but particular care is needed for coppice or perennial crops where protecting good crop regrowth is paramount[4]
- accumulate and carry the cut material on the harvester or transfer it directly to support vehicles
- design the crop field layout with long rows, sufficient turning space, and transport lanes
- choose machines with high road speed gear selections.

Land in some areas may be too wet for traffic access at certain periods of the year so it is essential to plan the harvest operation accordingly. The aim should be to maximise machine field capacity by minimising the down time when the machine is turning, being maintained etc. Having to stop to unload the accumulated cut material should be avoided. This requires good machine design, careful planning and a good crop layout. Where only a short harvest period is possible, long term storage of the biomass is necessary to supply the bioenergy plant all year round. This storage comes at a cost and so a trade off may be required between selection and planting of areas that offer good harvester access over long periods against costs for storage when harvesting cannot occur.

5.2.2 Width of cut

For many biomass crops the width of cut is variable and affects a number of other system and machine design parameters including:

- the work rate, in terms of ha/h
- capacity of other components of the harvester, such as an on-board chipper
- the number and width of passes made across the field
- wheel track settings across the width of the machine and any supporting vehicles
- for energy plantations, the tree row width and configuration of the plantation.

Tree crops, sugar cane, sweet sorghum etc. are normally grown in rows and so the machine is restricted to travel along the direction of the rows, usually harvesting one or two rows per pass. The cutting width of the harvester is limited by the planted row width. For example, harvesting of *Salix* in the northern hemisphere is normally achieved by cutting double rows at 750mm spacing as planted. (Figure 5-3)

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[4] Sims R E H, Lowe H T, & Maiava T (1994). All year round harvesting of short cycle crops eucalyptus. Proc. 8th European Biomass Conference, Vienna. 1, 507-514.

Figure 5-3 **Prototype willow harvester from Ireland cutting a double row in one pass and accumulating the sticks into bundles**

Cutting across the row direction where it is advantageous to do so, requires level ground without mounding such as around the tree seedlings when planted or wheel ruts. With vegetative grasses, cereals and oilseed crops not grown in distinct rows, the harvester cutting width is less of a design issue as the machine can travel in any direction (like a combine harvester in a field of cereals). Then the width of the cutting head relates mainly to the capacity of other parts of the machine to cope with large volumes of bulky and often wet material without blocking.

For tree crops in the northern hemisphere, a number of attachments have been developed to feed any protruding side branches into the cutting mechanism. For coppiced crops a major problem is that the cutting head must be designed to cope with single stems at first harvest but also with multi-shoot, wide stools in the older, coppiced crops.

5.2.3 Cutting mechanisms

Cutting mechanisms have a wide range of designs, the choice of which is affected by:

- forward speed, hence hectares or tonnes harvested per hour
- the maximum single stem diameter of tree crops at harvest
- the width between rows
- possible damage to perennial crops and coppice stools which could affect regrowth vigour, disease and plant mortality, thereby reducing the economic life of the stand before replanting becomes necessary.
- the selection of the cutting mechanism is governed by:
- for coppice crops, the anticipated width of the stools after ‘x’ harvests
- possible damage to the cut stems and resulting disease
- the frequency of re-sharpening the cutting blades.
- susceptibility to damage or wear from stones and soil
- the optimum cutting tip speed
- the ability to handle weeds, leaf litter, and trash.

Options available include:

- single disc or double disc with variable cutting teeth designs, diameter and speed of rotation (Figure 5-4)

- chainsaw -type chain cutters, needing relatively low power but with frequent sharpening requirements and tensioning to overcome chain stretch, a tendency to tear the tree bark and to block in weeds, and the risk of breakage and operator injury
- reciprocating knife, being either a single knife plus fixed fingers or double knives, both designs having a small maximum stem diameter cut (though some reciprocating knife hedge cutter designs can cut branches up to 125mm)
- hydraulic or belt drives with some slippage designed in to avoid breakages as might occur with chain and sprocket drives
- height of cut above ground which is usually variable to suit the crop and soil conditions (Figure 5-4) and also for coppice crops, if cutting higher up the stem is thought to result in more regrowth.

Hard surfacing of blades reduces the frequency of sharpening, as do blades with serrated edges, though these tend to block in weedy conditions. The cutting mechanism used governs the forward speed, particularly in woody crops, since the time to physically cut through a stem limits the travel speed over the ground. If the machine travels too fast there is a tendency to push the trees over.

Figure 5-4 **One type of design of feller cutting head for single stem harvest of large trees using a hydraulic grab to hold the cut tree during cutting before lying it on to the ground or on to a trailer**

5.2.4 Comminution

This process, which reduces the size of the biomass so that it can be used efficiently in a bioenergy plant, is defined as "the reduction of biomass by mechanical means to obtain a more uniform and valued bulk material". Breaking the biomass into small pieces can affect:

- the subsequent drying rate
- the bulk density
- the storage volume
- transport costs
- the need to screen to give a more homogeneous feedstock in terms of the particle size range, particular where this is critical to the process at the bioenergy plant.

Chipping, chunking or billeting (see 6.3.4) of whole plant material may require double handling if it is a separate operation. Keeping up with the machine's capacity is difficult when feeding it either manually or by using a grab. Dryer material is usually harder to comminute and hence consumes more energy per tonne of dry matter than when wet. The energy input per tonne of fuelwood product should be minimised by frequent knife sharpening, the moisture content of the materials, and the nature of the bark, especially if the bark is stringy. For a given size of chipper there is a maximum stem diameter it can handle. Keeping the comminuted material within an acceptable range of piece size produced is not always easy, and screening to remove fines, combined with recycle of any larger pieces may be necessary.

The form of the biomass received at the bioenergy plant is governed by the handling equipment used and the fuel specifications for the combustion or gasification equipment. The biomass feedstock may be comminuted at some stage of the fuel supply process, or left as whole stems or sticks and handled in bulk or after baling with large round or square balers. The options are many and varied and partly depend on the crop type.

Comminute in the field as part of the harvest operation:

- billet or chunk during harvest operation and then handle in bulk or in bales.
- chip during harvest operation and handle in bulk.

Comminute at the forest landing, headland or after temporary intermediate storage:

- leave as whole sticks and handle in bulk or as bales
- billet or chunk and handle in bulk or as bales
- chip using a mobile tractor-mounted chipper, hand fed or by a small grab
- chip using a large, transportable but stationary chipper.

Comminute at the conversion plant using fixed chipping equipment, or possibly a mobile version able to be moved on occasions between plants:

- receive as whole trees, branches or sticks and burn whole (for example, based on a US design of whole tree combustion plant)
- shred, billet, chip or grind (for co-firing with pulverised coal) on site before feeding
- receive as bales and either burn whole bales (as for straw, though usually shredded automatically first), or shred, billet, chip or grind
- receive as billets and burn direct or chip or grind
- receive as chips and burn direct or pulverise into grind.

Cutting and chipping in one-pass in the field has the practical mechanical attractions of easy and reliable handling. Chip harvesters are well proven in the wood chip and pulping industry. But this approach may create drying and storage problems if the biomass is stored for long periods before use. Chips of >20% moisture content (m.c.) can have rapid biological activity that may lead to:

- heating from respiration
- loss of dry matter
- mould formation
- operator health risk.

Hence chips are more acceptable if they can be taken off the farm or forest directly and used quickly by the bioenergy plant.

Billets have a lower surface area and cut area than chips, leading to lower respiration losses and less loss of dry matter. Various chunker designs such as a conical helix have been tested and show potential for billeting. Sticks, branches and stems dry naturally with little dry matter loss, but occupy more space and are harder to handle and transport. Therefore baling them has been investigated and is an alternative.

5.2.5 Transfer mechanism from harvester

The transfer mechanism of biomass material from the harvester affects the need for support trucks and trailers, the optimum length of row, and the harvester work rate. The type of mechanism used is limited by:

- the weight and volume of biomass that can be carried on the harvester
- the design and capacity of the support trailers available
- available access for trailers to follow the harvester in the field, which may be restricted by the terrain, cut stumps, soil load carrying capacity, other crops etc
- the soil type and moisture content.

The options available for the harvester designer are:

- for stem and stick harvesters and balers:
- to collect the material on board and discharge it on to the ground within the harvest site once the collection bay is full
- to retain bundles of stems or bales until the headlands are reached, then drop the material in stock piles or off-load bundles directly to awaiting trailers at the headland
- to off load stems, sticks or bales continuously by conveyor to trailers running alongside the harvester.
- for chippers and billeting machines:
- to accumulate chips / billets then unload at the headland
- to discharge the chips/ billets into a trailer pulled behind the harvester (Figure 5-5).
- to discharge chips/ billets into trailers running alongside the harvester.

Figure 5-5 **Chips being blown into a trailed bin which, when full, is hydraulically lifted and tipped into high sided trucks for transport to store**

Transfer of the biomass material to supporting trucks and trailers is more difficult on sloping ground. A continuous harvest operation without stopping to unload usually has a greater field efficiency in terms of hectares harvested per hour. For vegetative grasses, sugar cane residues, cereal straw etc, hay baling principles are well proven and worth considering. After transfer from the harvester, the material needs to be transported directly to the bioenergy plant or to storage.

5.2.6 Transport from the field

As with the supply chain stages already considered above, transport from the field can be by one of many alternatives, depending on the form of the harvested biomass. The choice affects:

- the overall harvest work rate
- the need for support vehicle/s
- the opportunity for transpirational drying if cut and stored as whole trees
- soil compaction if travel of heavy vehicles is not restricted to the headlands.

The method of transport is also affected by issues such as:

- the row length between the headlands at either end or limited access to the harvester's path due to other crops
- whether the cut material is dropped on to the ground to await collection
- the period before regrowth occurs in a coppiced crop
- any carrying capacity of the harvester
- the weight and capacity of the support vehicles.

Options include:

- carry the cut material on the harvester directly to the on-farm storage site and deposit it in stock piles
- collect whole cut trees or sticks from the field with (Figure 5-6) a grapple and trailer to collect whole cut stems and sticks from the headland
- collect and bale small whole cut trees or sticks from the field with a pick-up baler
- collect bales with loader/trailer from the entire field area from where they are dropped
- collect bales with loader/trailer, tractor front loader or fork lift from headland piles.

Figure 5-6 **Forwarder in Sweden with grapple and trailer for extracting forest arisings and small short cycle crop stems to the landing for chipping**

A range of trailers and transport equipment is available including:

- For stems, sticks and bales, a flat bed or forestry trailer
- for chips/billets, a bulk commodity trailer:
  - silage trailer with higher sides added, as biomass harvested for energy use is often a lighter material per given volume than wet green crops
  - high lift tipping trailer
  - roll on/roll off bins and trucks.
- for whole trees and branches, a trailer fitted with a grapple or a specialist machine with a simple means of compacting the load.

Sticks, branches and stems usually occupy more space and are harder to handle and transport than chips and chunks. Therefore baling could be an advantage where feasible, but it tends to be an expensive option. Transport can either be an integral part of the harvest operation or carried out subsequently.

5.2.7 Storage

In many situations the biomass will be stored prior to its use for bioenergy. Depending on the duration and nature of this storage it may affect:

- the quality of the fuel and its combustion characteristics
- the final total energy content available
- the final moisture content before combustion5
- the reliability of fuel supply for the plant over prolonged periods.

Storage of biomass is limited by issues of feasibility and cost, including:

- the initial moisture content
- the size of individual particles if restricting air movement between them
- the period of storage required
- ambient conditions during storage
- the land or building area available for storing the material
- the volume needed to be stored between harvests
- the availability of storage (ideally covered) at least for 2 or 3 days supply.

Intermediate storage of chips, billets or sticks is possible on-farm or in the forest. The material is then brought to the plant as required where it can be stored for a shorter period in a central store, readily available to the bioenergy plant in one form or another. The options include:

- uncovered storage on concrete pad
- uncovered on bare ground
- on concrete pad or bare ground, covered with tarpaulins or roofed structure
- uncovered, but then brought under cover into silos, open barn or A-frame building for last few days before use.

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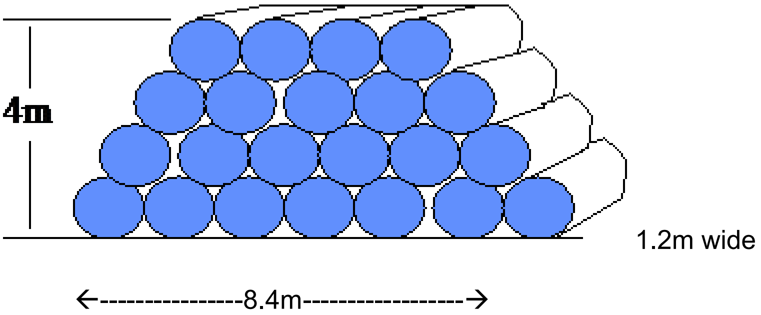
5 Nellist M E (1997) Storage and drying of arable coppice. Aspects of Applied Biology 49, 1-11.

The space needed for storage needs to be calculated for each plant as there can be high costs involved. Taking the storage of round bales as an example:

Stack 7+6+5+4 [4 bales high (4m) by 1 bale wide (1.2m) in rows] = 22 bales / 1bale row width



Floor area of 8.4m x1.2m = 10.08 m^2

For bales of 500kg @ 50 %mc, average storage density = 1.1 t/m^2 *(0.55 odt/m*^{2}*) of floor area;*

Storage volume of 8.4 x 1.2 x 4 = 40.3 m^3 *= 0.28 t/m*^{3} *(0.14 odt/m*^{3}*) allowing for stack geometry.*

For bales of 750kg @50 %mc, average storage density = 1.65 t/m^2 *(0.83 odt/m*^{2}*) of floor area*

Storage volume = 0.42 t/m^3 *(0.21 odt/m*^{3}*)*

Chips stored in piles 5 m high x 10m base width = 0.3-0.35 odt/m^2

Large scale chip storage at moisture contents greater than 20% can lead to biological activity, which may give:

- heating in the stack, loss of dry matter, and deterioration of the physical quality of the chips
- health issues when handling due to high dust and spore concentrations.

However, there are also many examples of successful chip storage, such as in the export wood chip industry where chips are stockpiled prior to being shipped overseas. In all cases, storage adds to the cost of the biomass that is finally supplied to a bioenergy plant. As such, storage should be considered as part of the overall system design, to balance issues such as:

- the benefits of operating a bioenergy plant all year
- possible difficulties in harvesting all year
- security of feed supply on a short term basis
- potential for drying the feed during storage.

5.2.8 Transport to conversion plant

Vehicles for transport from field or store to bioenergy plant help to determine:

- the catchment area to provide sufficient feedstock at the plant
- possible planning constraints due to number of daily vehicle trips
- the capacity of the transport vehicles used
- the number of journeys.

The selection of tractors, trucks and trailers is determined by:

- the average distance travelled to the conversion plant site.

- whether rail is available
- transport regulations regarding axle weights and vehicle widths and lengths
- road classifications for the proposed route to be taken
- the road width and traffic density
- handling equipment available at the collection and delivery points (Figure 5-7)
- the need to maximise payloads to minimise costs
- the means of securing loads.
- the maximum height of loads and length of truck-trailer combinations.

Figure 5-7 **Tractor/front loader unloading straw bales to place on conveyor within the building to feed a shredder and straw burner**

The options available depend on the nature of the biomass but include:

- chips in a high sided vehicle
- chips in bins on a flat deck truck / trailer
- billets in a high sided vehicle
- billets in bins on a flat deck
- whole trees or sticks in a high sided vehicle (possibly compacted after loading using straps or some form of hydraulic frame)
- whole trees or sticks strapped on to a flat deck
- bales stacked on a flat deck.

Bulk densities for different forms of biomass feedstock vary considerably, which impacts on the choice of transport. Typical examples (drawn from overseas experience) are shown below, noting large variations in biomass bulk density can occur between types and species.

1. **Whole trees and sticks** 0.10 odt/m^3 = 0.20 t/m^3 fresh wt (50% mc)

2. **Billets**

<u>220mm length</u> 0.14 odt/m3 (poplar) = 0.28 t/m3 fresh wt
0.125 odt/m3 (willow) = 0.25 t/m3 fresh wt

Note that in one trial after 250 days in storage, final bulk densities had changed to 0.155 t/m^3 for poplar @ 17.5% m.c. and 0.161 t/m^3 for willow @ 17.1% m.c.

<u>100mm length</u> 0.165 odt/m3 (poplar) = 0.33 t/m3 fresh wt
Note that after 293 days, final bulk densities were 0.22 t/m3 @18.6% m.c.

3. **Chips**

hardwood	0.174 odt/m3	= 0.35 t/m3 fresh wt
poplar	0.125 odt/m3	= 0.25 t/m3 fresh wt
spruce	0.125 odt/m3	= 0.25 t/m3 fresh wt
mixed species	0.162 odt/m3	= 0.35 t/m3 fresh wt

4. **Bales**

(500kg each @ 50%mc) 0.14 odt/m3 = 0.28 t/m3 fresh wt

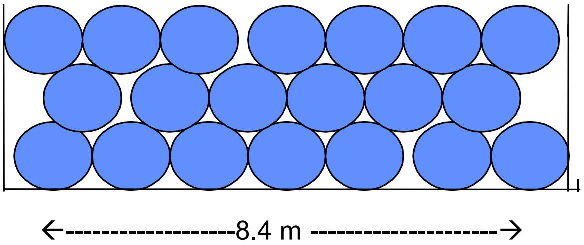
Changes in storage under Australian weather conditions may be quite different to the overseas findings described above. Also, it cannot be assumed that short cycle crops such as eucalyptus or willow will have similar bulk densities and weights as for forestry arisings at the same moisture content. For example, a special heavy duty Swedish prototype baler tested in Scotland was used to form biomass into round bales 1.2m long x 1.2m diameter (1.1m^3/bale) (Figure 5-8), and resulting bale weights varied by up to 50%:

lodgepole pine residues off a chain flail delimber	569kg / bale @ 35%mc = 0.37 odt/bale
sitka spruce residues	484kg / bale @ 31%mc = 0.33 odt/bale
lodgepole residues stump dried	391kg / bale @ 23%mc = 0.30 odt/bale
willow sticks from a short cycle crops crop	493kg / bale @ 49%mc = 0.25 odt/bale
willow sticks after natural drying	265kg / bale @ 11%mc = 0.23 odt/bale

Figure 5-8 Bales of willow sticks formed by a prototype Swedish baler

Based on a study of the transport of straw bales, it should be possible to produce 40 bales in an hour of suitable cut biomass material from, say vegetative grasses using a typical round or large square baler designed for hay and straw. An example follows for designing a bales transport system, using 500kg round bales at 50% moisture content.

A $60.5m^3$ capacity truck with a tare weight of 11.6t, 8.4 m long deck, 2.4m wide and with supports 3m high at either end, would hold 7+6+7 x 2 rows = 40 bales of 1.2m diameter at 3 bales high. The bales can be horizontal axis loaded using a tractor front loader.



40 bales = 20 t fresh weight payload

Volume of the truck = $60.5\ m^3$

Bulk density of the load = **$0.33\ t/m^3$**

If bales of 750kg could be produced, the bulk density would be increased to around $0.5\ t/m^3$. So 40 bales = 30 t fresh wt payload. But in this example the permitted maximum gross vehicle weight (GVW) of 38t would then be exceeded.

It is assumed that 30 square bales can be carried on the same 38t GVW truck. If the baler produces large, square bales of 880kg the maximum payload would be met. It would also be easier to stack the bales than round ones.

If the same 38 t truck was used to transport chips at $330\ kg/m^3$ and 50 % mc then a payload of 20 t would result; or even less with dryer chips. For whole trees and branches, obtaining a payload of more than 10 t would be difficult without some effective form of compaction. So for long distances, chipping can be a better option than transporting arisings or whole trees so long as long term storage is not necessary between transport and utilisation.

5.2.9 Drying the biomass

Drying the biomass may affect:

- the available energy content contained within the fuel
- the energy ratio of the system
- selection of bioenergy technology
- the ease of comminution.

Drying can be accomplished artificially or naturally (which takes longer but may be the cheaper option). Transpirational drying of whole trees is possible but only if cut when in leaf and extra costs from double handling may result. Where waste heat is available from the bioenergy plant some artificial drying may be possible, and this can be essential in cases where deterioration is expected to occur in storage if the material remains wet. The type of bioenergy plant determines the acceptable moisture content for the fuel.

The drying options for the fuel supply contractor include:

- transpirational drying of arisings or whole trees if leafy in the field
- natural ventilation in field store of billets, stems or sticks
- intermittent artificial ventilation in field store of chips or billets
- natural ventilation in central store of billets, stems or sticks
- intermittent artificial ventilation of chips or billets in central store

- raise temperature of artificial drying air using waste heat from plant
- raise temperature of drying air using gas or heat from a dedicated biomass burner.

Electricity consumption used for intermittent drying with fans running for only 6-8% of the time has been shown to be:

95 days:	Covered chip pile	3.72 kWh / odt
	Uncovered	8.51 kWh / odt
225 days:	Covered	5.23 kWh / odt
	Uncovered	10.63 kWh / odt

Drying chips by continuous ventilation of ambient air is not economic. Natural convective ventilation of the chips is not feasible as it does not prevent respiration and mould growth. Natural convection has been shown to cool both 200mm billets and whole sticks but both continued to respire and to lose some dry matter. For shorter 100mm billets, some ventilation may be necessary to avoid mould and to reduce dry matter loss.

Thermal bioenergy power plants often produce some waste heat which may be useful for biomass drying. However if the flue gases are cooled too much (e.g. by using a heat exchanger) they could condense inside the flue, leading to operational problems, corrosion and the possibility of unacceptable emissions.

There is a need to inhibit deterioration and dry matter losses during storage of biomass material for long periods of time so drying may be necessary for such extended storage. Where a range of fuel suppliers is used by a plant operator, there may be need for a buffer store from which the various fuels with their varying characteristics can be direct fed into the boiler to minimise local variations in moisture content. A payment system can be developed to offer a premium for fuels within the desired moisture content and particle size range.

Computer simulations have shown that drying chips with waste heat by continuous flow drying will minimise energy consumption and maximise drying capacity per m^2 of storage area. Getting the moisture level within 1-2% of 30% is easier than getting it down to within 1-2% of 15%. Drying wood from 50% to 25% removes 667kg of water/odt whereas to reduce it to 12% removes 864 kg. Remember that, while drying may improve the efficiency of the power plant, each type of thermal process is usually designed for feed of a certain moisture content. Using feed that is dryer than expected can actually lead to operational difficulties and emission problems.

6. Harvesting specific feedstocks

6.1 Summary

A pivotal issue for the economic viability of biomass energy crops is reduction of the cost of the harvested biomass fuel. This has resulted in the development and use of improved mechanised harvesting systems to reduce handling operations. This chapter provides an overview of several harvesting system options for specific biomass sources. Systems studies from overseas are the principal source of material for this chapter, and the general principles are applicable to Australian systems. Case studies for Australian systems are presented later in this report.

6.1.1 Plantation biomass

Plantation biomass may be harvested using a feller buncher, with a forwarder tractor, or purpose build forwarder used for extracting the biomass from the harvesting area. For steeper terrain, cable haulers are often used. These may be tractor or truck mounted. Harvested stems may be extracted from the harvesting area using a variety of skidders. Bed, grapple, tractor mounted and sliding boom processors are used to delimb and cut tree limbs into specific lengths for transport.

For comminution, several machine configurations are presented, from trailer-mounted chippers to self propelled vehicles. Energy used by chippers tends to increase with shorter chip lengths and lower moisture content, while the opposite applies to hammermills. The energy input into chipping is a very small fraction of the inherent energy in the chipped biomass (typically 0.5%). Chunkers or hoggers comminute biomass into larger pieces than chippers, with some advantages for drying.

Drying of the biomass fuel and its impact on the thermal efficiency of the bioenergy plant is considered. Further information on transpirational, evaporative, and forced-air drying is covered, noting the energy production benefits of combusting drier biomass.

For short cycle tree crops, harvesting technology has largely grown out of the agricultural sector, with equipment being adapted. For example, the German machinery manufacturer Claas modified a grass and maize forage-harvesting and processing machine that directly chips the biomass material as it is harvested, reducing the chance of soil contamination. Similarly an Austoft sugar cane harvester has been adapted in Europe for harvesting and chipping short rotation willow in one process.

Harvesting equipment needs to take into account the branching characteristics of the tree species to be harvested. Many eucalyptus trees have different branching characteristics from conifers.

For a 100 ha coppice eucalyptus crop[1], five harvesting options were compared including manual felling, a feller buncher, and both a large and a small forwarder. Extraction options were a tractor-trailer, tractor and chip bin trailer, and a large forwarder. The delivered cost of biomass varied considerably depending on the choice of equipment.

6.1.2 Bagasse

Millions of tonnes of bagasse (sugar cane fibre) are produced by the Australian sugar industry each year and can be used as an energy source. Use of cane tops and leaves could raise electricity-generating capacity in the sugar industry to over 1,000 MW. Supplementing cane wastes with woody biomass in the non-crushing season could theoretically expand energy production even further. However, removal of in-field cane harvesting wastes could be detrimental to nutrient balances, and further research is needed. Another possible development could be the move by the sugar industry to higher fibre cane varieties, to increase energy production.

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[1] Lowe H T, Sims R E H, & Maiava T (1994). Evaluation of a low cost method for drying fuelwood from short rotation tree crop for small scale industry. Proc. 8th European Biomass Conference, Vienna. 1, 461-467. Pergamon.

6.1.3 Cereal straw

Cereal straw, with potential disposal costs in some regions, provides another opportunity for bioenergy. Other agricultural residues including rice husks, maize cobs and nut shells are also potential feedstocks. Such residues tend to have low moisture contents in the range 10-30 percent (wet basis) and are therefore well suited for combustion. Evaluations overseas have indicated that there is little benefit to soil nutrient levels from returning straw into the soil. This has led countries such as Denmark to lead the world in using straw for energy production. However, straw is not yet used in Australia for bioenergy.

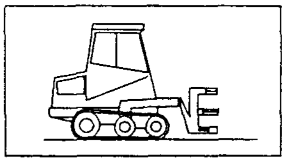
6.1.4 Energy crops

High yielding, energy crops and plants such as sorghum can store energy equivalents of over 400 GJ per hectare per year at a commercial scale, leading to very positive energy input/output balances. Similar analysis indicates that most oil-bearing crops only provide energy yield in the range 60-80 GJ per hectare per year. Nonetheless, biodiesel can provide good performance and reduced air and greenhouse gas emissions compared with mineral diesel.

6.2 Conventional forest harvesting

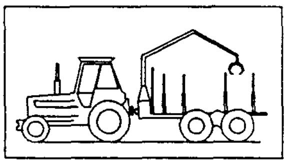
There are several methods for harvesting trees in use worldwide, the manual chainsaw remaining the most common. However due to safety reasons as well as economic ones, there is a trend towards more mechanised systems. Once cut, the material has to be removed from site and many designs of extraction machines are available for use on a wide range of terrains and with various sizes and species of tree. What suits one forest may not suit another. Some common designs are shown below. These methods could be easily adapted to harvest energy plantations where the trees are as large as traditional forest crops. More likely is that the stemwood will be extracted after harvesting by traditional techniques then the arisings can be collected for biomass.

Harvesting can be by manual chainsaw, or by feller-buncher with a chainsaw-type cutting head or a hydraulically actuated guillotine type cutter.

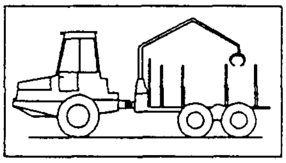


A feller-buncher is a purpose-built forest vehicle with front-mounted felling and accumulation head which cuts the trees and holds them until dropped on to a site ready for collection.

Extraction of the cut material from the forest to a road or to a “landing” for further processing can be accomplished in numerous ways.



A *forwarder tractor* is a four-wheel drive agricultural tractor with linked trailer and grapple which extracts shortwood, logs, and cut stems and small trees entirely clear of the ground.

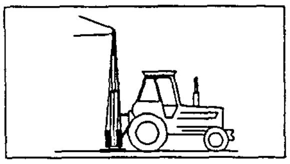


A *forwarder* is a purpose built, frame steered forestry vehicle with integral timber bunk and grapple to load the logs or trees (Figure 6-2).

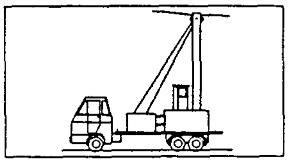
Figure 6-1 Forestry logging trailer with hydraulic loading boom and grapple which can be operated behind a standard agricultural tractor

Figure 6-2 Specialist forestry forwarder with articulated chassis

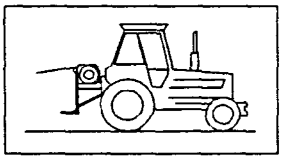
Cable haulers are used to extract forest material on steeper terrain where wheeled vehicles cannot safely go. Costs are higher and, unless pulled out as whole trees, extraction of harvests is not economic.



A *tractor mounted cable crane* uses a tower and tractor power take off (pto) for a drum winch, and is capable of extracting loads of stemwood or whole trees on steep country being totally or partially clear of the ground.

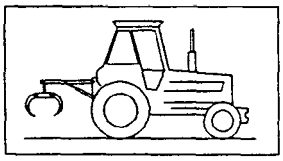


A *truck mounted cable crane* tower with drum winch is also capable of extraction of loads totally or partially clear of the ground but is normally of greater load capacity than tractor-mounted systems (Figure 6-3 and Figure 6-4).

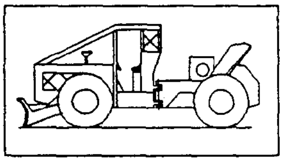


Skidders are simple machines designed to pull harvested stems or whole trees to the landing for further processing and/or loading on to transport vehicles. They are usually capable of extracting whole trees by lifting one end of the load clear of the ground during extraction. Even so, soil and stone contamination is often a problem.

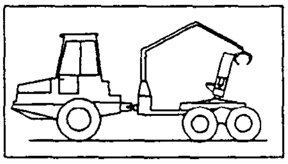
An *agricultural tractor winch skidder* is a four-wheel drive forest tractor fitted with rear-mounted winch powered by the tractor's power take-off.



An *agricultural tractor grapple skidder* is also a four-wheel drive forest tractor but fitted with a rear mounted skidding grapple.



An *articulated winch skidder* is a purpose-built four wheel drive, frame steered, forestry vehicle with integral drum winch (Figure 6-5)

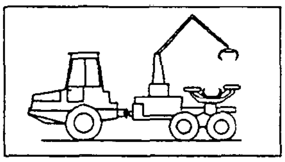


A *clam bunk skidder* is a purpose-built frame-steered forestry vehicle with bunk mounted hydraulic clam and integral grapple.

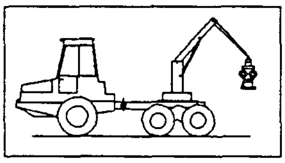
Once the whole trees have been delivered to the landing, various designs of processors are used to strip the limbs from the stemwood, to cut off the tops, and to cross cut or "section" the stem wood by cutting it to desired specific lengths. The logs are then ready for transport to the processing plant. The residues left at the landing may be returned to the forest, burned, or collected and used for bioenergy when they are normally chipped and transported to the heat or power plant.

Figure 6-3 Cable hauler tower in *P. radiata* plantation extracting whole trees down to landing for processing. (Note bulldozer used for anchor only)

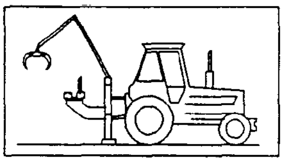
Figure 6-4 Cable hauler extraction of logs in steep terrain up to a landing for removal by transport vehicles after sectioning to length (here shown manually)



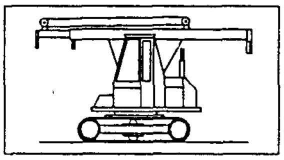
A *bed processor* is a two grip unit mounted on a forwarder chassis and capable of delimbing and cross cutting whole trees to specific lengths.



A *grapple processor* is a single grip unit mounted on a forwarder chassis or on a semi-portable fixed platform (Figure 6-6).



A *tractor mounted processor* is a two grip bed processing unit mounted on an agricultural tractor.



A *sliding boom processor* is a purpose-built processor, capable of delimbing and cross cutting but not always to specific lengths (Figure 6-7).

Figure 6-5 Articulated winch skidder working in poorly managed 30 year old *P. radiata* plantation with a large proportion of material suitable only for bioenergy use

Figure 6-6 A grapple processor delimbing, topping and sectioning stemwood to desired lengths

Figure 6-7 A sliding boom processor at a landing, delimbing logs

6.3 Short cycle tree crops (SCC)

Whether the biomass is grown as a single stem or coppice regime, or is a by-product of a crop grown primarily for other purposes, harvesting it and collecting it from the field is a key operation. Manual chainsaws may be satisfactory for small firewood plots (Figure 6-8) but on an industrial scale, mechanised harvesting machines should be used where possible, particularly units that are reliable and well tested. Using such machines can help spread the fixed ownership costs over more hectares and longer harvesting seasons.

Figure 6-8 Harvesting large or small trees (or in this example, 3 year old coppice *Eucalyptus* regrowth) can be done manually using a chainsaw with varying cutter bar lengths to suit the tree stem diameter

One of the key aspects to successful biomass production systems is matching the right harvesting machinery and method to the type of plantation. The method of harvesting can have a large effect on the sustainability of short cycle tree crops, the total biomass produced, and the overall cost and feasibility of growing SCC.

Harvesting of single stem, short cycle tree crops for pulpwood using variations of conventional forest harvesting systems is not currently practised in Australia. However, it is common practice in parts of the northern hemisphere and so the discussion provided in this chapter is based almost completely on overseas examples. There are few purpose-built harvesting machines commercially available for use with SCC but due to increasing interest in SCC as a source of fuelwood and fibre, new machines are being developed. Machinery adapted from agricultural crops is being used to harvest predominantly small stemmed crops such as *Salix* (willow) grown in Europe, Scandinavia, UK and Northern America. Other machinery derived from forestry origins is being used to harvest larger diameter SCC trees mainly for fibre production in places such as southern USA, Central America and South Africa.

The information provided here shows that harvesting many forms of SCC biomass is already quite feasible, and that a number of alternative harvesting methods exist. Equipment selection must be on a case-by-case basis. The particular methods applicable to Australian SCC biomass may be similar to methods and equipment used overseas, however they must also take into account attributes of the trees (particularly multi-stemmed evergreen eucalypts as opposed to single stem, deciduous willow), the planting patterns, quantities required and so on. Additional information on harvest of Australian eucalypts is provided in the mallee case study later in this report (see chapter 9).

Specialised equipment for felling and bunching SCC can be used to harvest, then accumulate, bundles of small diameter trees (Figure 6-9, Figure 6-10 & Figure 5-3). Direct harvest/chip machines like the Claas forage harvester (Figure 6-11) are being used commercially in Europe for the production of willow fuel chips but are yet to be evaluated with other species and under different conditions.

Figure 6-9 Feller-buncher with accumulating head developed for SCC harvesting of poplars in the USA

Figure 6-10 Canadian FB7 prototype harvester developed for harvesting SCC poplar trees with stems up to 7 inches (175mm) diameter

Figure 6-11 **The Claas forage harvester with twin disc cutting head developed to harvest SCC willow**

6.3.1 Selection of harvesting system

The decision as to which harvesting method to use will often be a compromise between maximising sustainable yields and minimising costs for any given location. The issues to consider during harvesting are the immediate and long term effects from stump damage, soil and root compaction, and damage that might be caused to unharvested trees or adjacent crops. Consideration must also be given to the form in which material is required for further processing.

The harvesting system must be considered at the outset of any integrated bioenergy project development, as it is closely associated with the tree selection and growth strategy, and with the delivered costs of biomass. This would also allow the careful planning of row width and access ways based on the physical requirements of the harvesting equipment. When deciding on suitable equipment, consideration must be given to:

- the resource (wood/tree) characteristics
- desired end product characteristics
- terrain characteristics
- scale of operation.

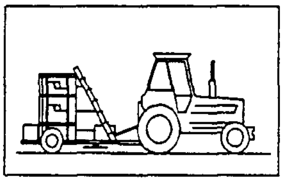
Machines that directly chip the biomass material as it is harvested rather than drop it on to the ground reduce the chances for soil contamination. However these machines are often heavy and may create soil compaction problems, especially on wet sites. The condition of the site after harvest can influence the vigour of regrowth and the chances of disease build up. Material left on site can create an ideal environment for encouraging disease and impeding regrowth. Also the land use and condition of the site prior to harvesting will influence the felling and extraction techniques.

Harvesting and processing can be performed separately, or integrated into one continuous process. In Sweden and the UK agricultural machines like the Claas and the Austoft sugar cane harvester have been adapted to harvest and chip SCC willow in one process. Other machines (Figure 6-9) cut and bundle coppice material for further processing at a later stage.

Short cycle crops tend to have many smaller trees and harvesting them individually can be a problem. Traditional forest thinning machines can be used and also feller-bunchers but the work rate or productivity in terms of t/h or ha/h is generally slow and hence expensive in terms of $/GJ harvested. Harvesting multi-stemmed coppice regrowth, as opposed to single stem trees, can be even more problematic. The base of the tree can increase in size with age as more stems are produced after each harvest. Very few commercial machines exist, but many prototypes have been evaluated, including for mallee eucalypts[2].

Figure 6-12 Hydroaxe feller buncher harvesting poplars

The challenge to harvest other coppice crops such as *Populus* or *Eucalyptus* has yet to be resolved satisfactorily. One additional problem is the need to minimise damage to the cut stool in order to reduce fungal infestation and tree mortality and to encourage shoot regrowth. A number of prototype machines have been developed.



A *coppice harvester* is a purpose-built unit, powered and drawn by four-wheel drive agricultural tractor or self-propelled and capable of felling, bunching and processing of coppice stems.

Harvesting has to be carried out efficiently and with the right equipment to minimise costs. Specialised machines that offer high productivity and efficiencies also tend to have high capital costs, so they must be kept operational as much as possible, which is often impractical. Less specialised equipment like a chainsaw, can terefore be cost competitive even though more labour intensive, though productivity and efficiency may be compromised.

Weight reduction of a load can be achieved by allowing felled trees to transpirationally dry on site before extraction. This practice is also beneficial when weight restrictions limit the amount of material that can be transported on roads.

The size and type of machinery used in SCC harvesting will be influenced by the general shape and growth of the trees. Typically the growth form of *Eucalyptus* trees is different from traditional coniferous forests such as *Pinus radiata*. Generally eucalypts have the bulk of their crown concentrated towards the top of their bole (stem), with the bole having a gradual taper so that the

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[2] Mallee harvester to energise row-cropping (2010). http://grdc.com.au/director/events/groundcover?item_id=552D1221CCB66BBBEB5CE1359AA17D28&article_id=65291145C5240E7CFD5D6FACAB3B7146

centre of gravity is higher than that of pines. The height of a *Eucalyptus* tree for a given diameter is also generally greater than comparable coniferous trees. As a result of these factors the crown can exert a greater influence over the direction of fall when the tree is felled. This may create problems for conifer forestry machines when harvesting large *Eucalyptus* trees.

The branching characteristics of *Eucalyptus* trees may also require a different delimbing technique than coniferous trees. Traditional delimbing heads may not work effectively on some Eucalypts because of the smaller angle between the stem and branches.

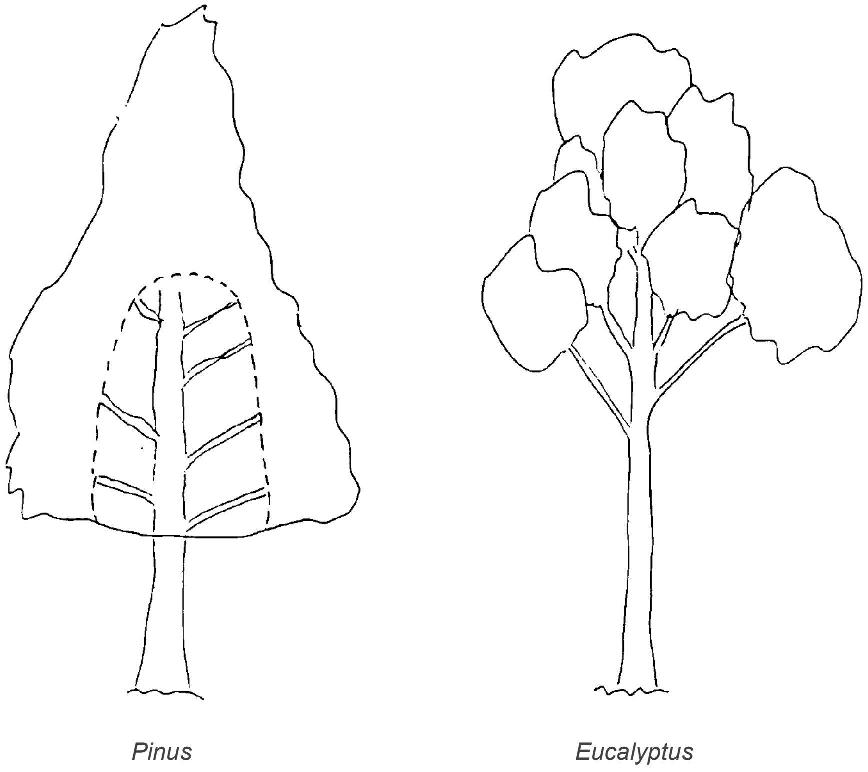


Figure 6-13 Structural differences of Pinus vs Eucalyptus

Manual felling techniques using chainsaws can be inexpensive, simple and versatile, whereas fully mechanised systems of harvesting SCC (i.e. felling and bundling or harvesting and chipping) are being used more commonly overseas. Different crop factors such as species and stocking rates, and different terrain characteristics, can have a significant effect on the productivities of these machines.

One other factor that may affect harvesting productivity is the presence of foliage. The majority of northern hemisphere machinery has been developed for harvesting deciduous SCC crops in the winter, when leaves are absent. Eucalypts maintain their leaves all year round so machines must be able to harvest trees in full foliage, which can be more challenging. Seasonal harvesting in Europe means that year-round operation of bioenergy plants relies on extensive storage of biomass, whereas in parts of Australia the ability to harvest of eucalypts almost year–round means that there is potentially less demand for storage either in-field or at the bioenergy plant.

SCC production systems currently in use overseas may have to be modified before they could be used on a commercial scale in Australia. For example in Sweden willow trees are now grown in paired rows, and at higher densities to provide easier and quicker harvesting using a Claas forage harvester.

It may be that specialist machines like the Canadian FB7 harvester (Figure 6-10) could only be operated satisfactorily under a limited set of conditions and with selected SCC crop species after considerable modifications, whereas direct harvest/chip machines may work well under a range of current SCC management practices. These machines appear to be an attractive option because of their `single pass' operation, but wet chips result. A two pass operation could have benefits of allowing on-site transpirational drying prior to extraction and reducing the power requirements of the felling machine, requiring smaller and less expensive equipment. Harvesting costs may be reduced, however transport costs may be increased by the need to make a separate pass for collection of the harvested material and soil contamination may also increase.

Under current popular eucalypt SCC management practices, a single stem is harvested at the end of the first cycle. During successive cycles multiple coppice stems need to be cut from the initial stump. Over this period the stump width can increase significantly. Most current harvesting machines operate over a relatively narrow range of diameters so that variations in stump diameter over time, and a large number of small stems, may cause difficulties and hence reduce efficiency for harvesting operations.

6.3.2 Harvesting machinery options

As an illustrative case study, five harvesting options were identified and analysed for a 100ha coppice eucalyptus crop grown in New Zealand.

- *Motor manual*
  Felling using two chainsaws and two persons. For compliance with the NZ Health and Safety Act a minimum of two people must work together in the felling operation at any one time.

- *Feller-buncher*
  A machine that physically holds the tree then cuts and places it in a pile. There are several forest machines available which are suitable. A tracked excavator would minimise ground damage while having adequate traction, especially in the wetter areas of the plantation. However there are considerable costs associated with maintenance of tracked machines and an excavator would be confined to moving only up and down rows to avoid stump damage when crossing them. It is possible that flotation tyres could be fitted to improve manoeuvrability and minimise damage but they might be subject to side wall damage from the cut stumps.

- *Large forwarder*
  A forwarder adapted to harvest the trees and extract to a landing site. There are only a few of these machines available. They may be too expensive if there are relatively short transport distances within the 100ha plantation and high annual costs. They may be better suited to larger plantations.

- *Small forwarder*
  A tractor towing a forestry trailer with feller/grapple saw mounted on a hydraulic arm to harvest the trees and extract in a similar way to the large forwarder but at a slower rate.

- *Contractor*
  Employ a contractor to undertake the felling using any of the above methods for harvesting, extracting and chipping the trees. However, there is a lot of uncertainty as to the actual costs involved in the operation in regions where it has not been previously undertaken. If several plantations in close proximity were available for harvesting during the year, the greater quantity of work would make it a more economical proposition for the contractor to invest in necessary equipment. Then the machinery could be specialised and still operate for longer periods. Initially the cost quotes and productivities supplied and calculated can only be estimates as it will take at least one harvesting season before an accurate assessment of the actual methods and productivity can be obtained.

6.3.3 Extraction and transportation

The method of harvesting and the final usage of the material can influence the extraction method. It is undesirable to have biomass that is contaminated with soil because of difficulties that soil can create before, during and after combustion. Small, whole trees and billets offer advantages during extraction by forwarders (self propelled logging trailers) by minimising the risk of soil contact and contamination, because they can be lifted from their felled site, rather than dragged. Forwarders are capable of moving through a plantation, depending on the tree spacing, and removing selected material. It is also possible to fit a felling mechanism to the grapple arm to allow both felling and extraction of the thinnings to be integrated into a single process. Forwarders are becoming common in forestry operations mainly for collecting residual material and small wood pieces, but they can also be used for extracting timber logs. Logging trailers pulled by agricultural tractors can perform similar tasks to a forwarder but at a lower productivity rate.

Extraction is the relocation of the trees or biomass material from the plantation. Four options for this process are feasible and can be incorporated into, or run in conjunction with, the harvesting and comminution operations.

- *Tractor and trailer*
  Use a tractor and forestry trailer to transport the whole trees from the plantation site where they are felled to an intermediate storage area or direct to a chipper.

- *Tractor and chip bin trailer*
  Use a tractor and bin trailer to extract chipped material from the plantation to the silo or shed where chips will be stored.

- *Large forwarder*
  Use a feller-forwarder for transporting whole trees. The same reasoning applies as for the feller-buncher in harvesting option 3. In a larger plantation the forwarder without a tree felling unit could be suitable for just extraction.

- *Contractor*
  Use a contractor to extract the trees. This will more than likely be incorporated into a harvesting operation, and may offer machinery that is well-utilised across several sites in addition to the one in question.

6.3.4 Comminution

One of the first steps in using biomass for energy is processing the raw material into a form that can be utilised efficiently as fuel. Raw material, being whole trees, forest residues, cereal straw etc, needs to be converted to a state that enables it to be easily and consistently handled. Forms of biomass used in the energy conversion process include billets, specially ground material, wood chips, chunks, briquettes etc.

The end use of the product and the energy requirements should be considered when selecting a comminution form or technique most appropriate for an individual situation. Comminution is usually carried out by one of two main techniques. The first involves chipping or chunking when using sharp cuttings edges to cleave or shear the biomass into smaller pieces. The second method employs a blunt impacting tool to crush or shred the material, producing particles of indistinct geometry. This latter process is usually called hogging or shredding.

The strength of the wood affects the power required to reduce it from solid wood pieces to chips or chunks. A wide range of comminution machines exist such as chippers, hammermills and shredders. Each type consumes different amounts of energy per tonne of biomass processed. Those with sharpened edges to the cutting blades need regular maintenance to minimise energy inputs.

It should also be noted there is a strong interaction between the particle size of the biomass, the ability to minimise transport costs by maximising payloads, and the rate of burn, fermentation, hydrolysis etc. depending on the conversion system used.

(i) Chippers

Chipping equipment ranges from large stationary machines developed for the pulp industry, down to small tractor-operated designs suitable for on-farm use for woodlots. Selection of comminution equipment should fit into the overall handling and delivery system and relates very much to end product specifications.

Energy inputs of chippers tend to increase with shorter chip length and lower moisture content, whereas the reverse is the case with hammermills. Hardwoods, with shorter fibres, tend to require more energy than softwoods to produce the same size chip. Over a range of machines, moisture content and materials, the energy input needed to comminute one oven dry tonne (odt) of roundwood (logs) to 25mm nominal chips ranges from 5 MJ to 250 MJ. Since 1odt contains approximately 20 GJ (20,000 MJ) of available energy, comminution is only a small proportion of the total. Minimising the energy input is important, but it has to be balanced against cost and time. The chipper machine productivity in terms of tonnes processed per hour is an important selection criterion, as are the maintenance costs and the capital cost.

Due to the low bulk density of unprocessed woody biomass, transport costs can be considerable. To increase the density and thus reduce transport costs, whilst at the same time improving the handling and combustion properties, processing the biomass into a higher bulk density and more uniform state is often required. At times this can be through comminution, though for some biomass forms (such as reject logs and even straw) this process may actually reduce the bulk density.

Tree diameters, stand volumes and species affect chip size for any given method and production goals affect the size of comminution equipment required for a given system. The quantity and quality of the raw woody material varies with tree age, species, moisture content and the components present (ie stem, branches, leaves). As a result many different forms of comminution equipment are available, each suited to converting a particular raw material to a processed biomass feedstock with a distinct particle size distribution and fuel quality.

Disc and drum chippers can produce chips with varying size and dimensions, with variations achieved by altering parameters such as the pitch or angle of the blades, the number of blades, the speed of the material being fed in, anvil clearance, and disc rotation speed. To obtain a uniform particle size and maintain an even workload on the chipping blades and motor, in-feed rollers are used to control the rate at which the wood is fed onto the cutting surfaces. If the rotational speed of the chipping blades slows, the machine’s ability to blow the chipped material out the discharge chute is reduced and blockages can result. Many chipper designs have the forward speed of the feed roller dependent on the fly wheel or drum speed to reduce the chance of blockage and maintain an even work load on the motor by allowing sufficient fly wheel speed to be maintained. This gives improved uniformity of chip size.

The blade orientation of some chippers produces an inward pulling effect, thereby reducing the need for feed rollers. However, it is advisable to have feed rollers on the machine when chipping brushy material, such as whole eucalyptus trees with leaves and branches, because without them the irregular nature of the material can produce uneven chip sizes and cause the motor load to vary. However the majority of small chippers do not have feed rollers because the final use for the material (or chip quality) is not critical and the cost of adding rollers would substantially increase the total cost of the machine.

(ii) Chunkers

The concept of chunkwood was developed to improve the utilisation of small trees and forest residues and because drying studies indicated that there are advantages in having particles larger than chips. Chunking requires less energy than chipping. It can provide a denser material for storage, trucking and hauling (and so requires less storage volume), and it permits better drying during storage because of larger air spaces between the chunks. Chippers have difficulty producing chips with lengths greater than 70mm whereas chunkers can produce blocks 50 to 250mm long, though the cross-sectional area is very variable. Chunks are produced by sharp knives making regular cuts into the material which is fed in at a controlled rate. There are two main chunking methods; spiral head (or cone screw), and involuted disc chunkers.

(iii) Chip and chunk quality

The comminution method used has a large effect on chip quality, one of the most important factors being moisture content. The comminution method and moisture content together can affect the drying and storage characteristics of the material, which inevitably affects the fuel quality (though there are many other factors used to evaluate the quality of fuel).

A quantitative standard for classifying fuel quality with respect to its handling and burning properties would be very useful. However, a classification system would be difficult to establish because of the variety of fuel particle types required by different energy conversion systems. The ability of a furnace to burn various types of biomass depends on its design. Some combustion units are exclusively wood chip burners, whereas others are suitable for burning combinations of wood chips, bark, sander dust, straw, coal etc. Bark and foliage, along with other irregularly shaped material such as oversized chips and twigs can create mechanical problems for handling equipment, and possibly cause blocking of conveyers and storage silos.

In the products from any comminution process, apart from the material with the required particle size range there will also be some smaller and larger material. Comminuted woody material can therefore broadly be divided into three major size categories:

1. acceptable material

2. fines (undersize)

3. oversize.

- ***Acceptable material*** is suitable for the final end use, its dimensions being within a suitable range. Requirements for pulping (for the paper industry) may be different from those for combustion, and the latter requirements will also vary according to the design of the bioenergy unit being used.

- ***Fines*** are comprised of small components including bits of bark, foliage and inorganic impurities. Chips produced from SCC whole trees, forest arisings and stumps can have a high portion of fines, and the effect of this fine material on the end use of the material is variable. For fuel use, chip bulk density is the most critical characteristic. Foliage and soil content can have an effect, whereas bark contamination is not normally a problem, though it is for pulp chips. By reducing the portion of fines in a biomass feed stream, more air can circulate through a pile of chips aiding moisture loss, minimising temperature and micro-organism increases, and consequently reducing biomass losses.

- ***Oversized material*** is typically too large for its desired end use and is excluded by a screening process based on size (length and/or diameter) and sometimes weight. A high proportion of oversize chips can be produced when small diameter, often dry and stringy material, like branches and forest arisings, are comminuted. This can create problems for conveying equipment and cause bridging in silos and hoppers. Oversize material generally presents a greater problem to smaller scale installations, where material flows are not large and openings are narrower. Also the separation of the oversized material is often less effective when using cheaper, small scale screening systems.

To reduce biomass wastage and handling difficulties it is normally recommended that there should be uniform material size. Reducing the portion of oversize material will help to minimise handling difficulties by reducing bridging and decreasing the angle of repose.

Remember that most types of solid biomass fuels have low energy densities compared to fossil fuels. As a result, the volumes that have to be handled per energy unit are often larger than in the fossil fuel industry. This means that storage areas and handling equipment have to be relatively larger to maintain the same energy output capacity. However, the size of an intermediate storage facility prior to the boiler or gasifier is often more dependent on the rate of fuel supply required and issues of feed continuity.

(iv) Screening

Screening involves separating two or more fractions of material on the basis of size and/or weight. Screening can be difficult with biomass because of considerable variation between crop species and with other factors such as moisture content. Raw or unclassified material generally requires two screenings to firstly remove the large oversize material and secondly to remove the smaller fines. The greater the difference between any two wood fractions the easier it is to separate them. However, with most screening operations there is some overlap which will produce a small percentage of impurities in the pure fraction.

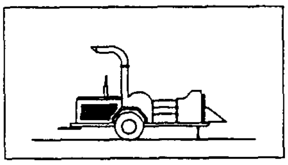
Screens are either flat vibrating designs or rotary drums. The shape of the holes in a screen can influence the quality and size distribution of the chips. Round screen holes will produce a product with a more constant size compared to square holes. Square holes have a diagonal size 1.4 times the nominal side length and produce a product that is then dependent on how it is presented to the screen. Despite this, square holes enable a larger percentage of the screen to be open to sieve the material, as round holes do not interlock and therefore present greater surface area/m^2 of screen.

The vibrating or rotating speeds of a screen have an effect on screening efficiency, however the efficiency is also dependent on the type of screen being used and other factors such as moisture content and portion of oversize/fines. Screening of the fuel is also possible between storage and the bioenergy plant to ensure a consistent quality enters the main plant feed system.

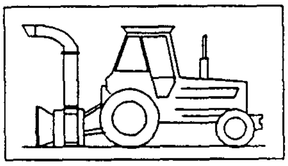
Solid biomass with a low moisture content tends to have better handling characteristics than wetter biomass. This complements the need for dry wood to reduce storage losses and thus maximise energy conversion. Dry chips require smaller holes and less agitation to screen than wetter chips thus aiding accurate classification. However excessive agitation of dry chips can increase losses by forcing marginal chips into undesirable categories and increasing the portion of fines from the physical breakdown of these chips. Excessive agitation of dry chips can also cause an increase in fines and create more dust.

(v) Types of equipment

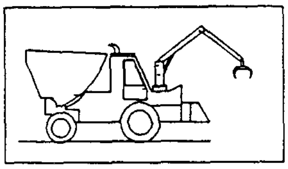
Various forms of chipper are commercially available for adaptation to bioenergy applications.



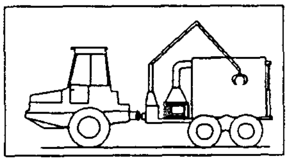
Trailer mounted chipper being a comminution unit with integral power source rather than being connected to a tractor power take-off.



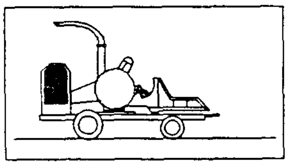
Tractor mounted chipper being a comminution unit powered from the tractor power take-off.



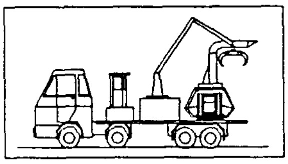
Self-propelled chipper being a purpose built forest vehicle with front mounted grapple to feed the chipper unit, and with a rear mounted chip bin.



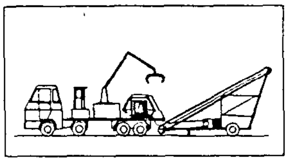
Forwarder mounted chipper being a large self-propelled comminution unit with integral power source and chip bin, mounted on a forwarder chassis.



Heavy-duty trailer mounted chipper being a large comminution unit with integral power source mounted on a heavy-duty chassis and trailed by truck or forest vehicle.



Truck mounted chipper being a large comminution unit with integral power source and grapple, mounted on a truck chassis.



Chunkers can be in similar format to the chippers above but there are fewer commercially available machines.

The most common is a *truck mounted chunker,* being a large comminution unit with integral power source and grapple, mounted on a truck chassis, and used in conjunction with an elevator for loading the chunks, which are too heavy to blow.

Examples of these pieces of equipment are presented in the following figures.

Figure 6-14 Trailer mounted chipper with auxiliary power supply (also available in smaller sizes than shown)

Figure 6-15 Tractor mounted chipper for small-scale applications at 5odt/h and fed by grapple or manually

Figure 6-16 Using large mobile chipper to collect and chip *P. radiata* plantation thinnings

Figure 6-17 Heavy-duty chipper handling SCC poplar at around 30 odt/h with grapple feed

6.3.5 Drying the biomass fuel

As has been noted above, there is a strong interaction between moisture content, transport, storage and conversion of biomass so it is worth briefly returning here to discuss drying the biomass as part of the supply chain process. When using wood, which naturally contains significant amounts of water, the heat required to raise the feed temperature and evaporate the moisture generally has to be generated by the wood itself. Since a typical heat plant (furnace or boiler) is designed to maintain sufficiently high exhaust gas temperatures to avoid condensation in the stack or chimney, much of this exhaust heat is usually not recoverable (though there are exceptions such as condensing turbines) (Figure 6-18). Hence the thermal efficiency of the overall bioenergy system will be reduced when using fuels of higher moisture content. The heat lost in the exhaust gas is also directly attributable to the moisture content of the fuel, which directly affects the efficiency of the system. The loss will vary from <2% of the total heat input when the fuel is at around 8% m.c., to nearly 15% when the fuel is at 50% m.c. So, for greater efficiency, the drier the biomass fuel the better. In addition, losses in thermal efficiency occur due to unburnt fuel being carried into the ash (possibly 0.5% loss) and surface heat loss from the actual plant of around 3% (but which varies with the plant design, and extent and temperature of the external radiating surfaces).

Figure 6-18 Drying a two-day supply of fuelwood occurs in the 'A Frame' building using waste flue gas heat at a 30MW wood-fired power generation plant in the USA

In addition to the fuel moisture content, biomass contains hydrogen atoms which react to form water during the combustion process. The heat required to raise the temperature and evaporate this "extra" water also becomes unavailable to the system and has a similar effect on the overall heat recovery efficiency. The effect on the combustion system efficiency of both the free moisture and that formed by combustion of the hydrogen has been calculated (Table 6-1).

In many combustion plants the biomass feed is received fresh at approximately 45 - 55% moisture content and is used at that moisture level. However some biomass feed is initially received at moisture contents of 60% or more, which requires pre-drying to facilitate combustion. In other bioenergy plants, reduced moisture contents are required, for example fast pyrolysis where the ideal moisture content of the feed is be less than 10%. In these circumstances most biomass feeds require drying before use.

Table 6-1 Typical heat losses during combustion due to the moisture content of the biomass fuel and combustion of the hydrogen contained in the fuel

Fuel moisture content (% wet basis)	Resultant energy losses %
0	19.6
10	20.9
25	24.8
40	30.2
50	34.5

The environmental ambient conditions, (mainly temperature, air movement and humidity), together with particle size and the structure of the tissues of the specific biomass, determine the release of moisture from the biomass by transpiration and evaporation, and the rate of release.

- ***Transpirational drying*** is the loss of water via the foliage of the plant. It occurs continually whilst the plant is growing. For example, 4 – 5 m tall, three year old *Eucalyptus saligna* trees grown as short cycle crops, can each transpire over 30 litres of water during a sunny summer day, or approximately 2 – 3 l/day when it is overcast and cooler. Transpiration can continue for some time after trees are harvested, a process which can be utilised to lower the biomass moisture content with minimum cost inputs.
- ***Evaporative drying*** is the loss of water from the cavities of plant cells, which occurs mainly as a result of evaporation of the moisture present. Energy is required to evaporate the water during the drying process. When only the moisture in the cell walls remains, this is known as *fibre saturation point* and is normally between 20 – 26% m.c. As fresh biomass dries, using either solar or artificial energy to heat the drying air in order to carry more moisture away before it becomes saturated, the 'free' water in the cell voids is lost first. Below the fibre saturation point, additional energy is needed to release the water molecules, which are held hygroscopically in the cell walls. This energy requirement amounts to 2.43 MJ per kg of water evaporated.

Evaporative drying can be achieved by the natural ventilation of air passing through the biomass when stored outside in piles, or by using forced air flows from fans through biomass stored in buildings with controlled ventilation. Natural drying depends on weather conditions and hence takes longer and is harder to control. A large storage area for woody biomass is usual (in the open) as drying may take weeks or even months. The drying biomass represents an investment tied up for this period. Concrete pads are preferred as a base for storage and the biomass must be set down and picked up again (as opposed to being taken straight from the field to the bioenergy plant for use).

If forced air drying is used it needs controls, and is capital and energy intensive. However, particularly if heated air is used, it may take only hours not weeks to reach the same optimum moisture levels. The decision to install such drying systems can be made on the basis of comparing its capital and operating costs with the financial return from efficiency gains via use of a dryer feed.

The rate at which drying occurs to fibre saturation point varies with plant species, ambient temperature and humidity and, for woody biomass, whether or not there is bark cover left on the logs and branches. Any further moisture loss down to the *equilibrium moisture content* is slower. This is the point at which the moisture content of the biomass is in balance with the relative humidity of the surrounding air, so it will normally vary around 10-15% m.c. day by day.

The smaller the piece size the greater the surface area / volume ratio which favours faster initial moisture loss. In woody biomass, the cells are longer going "with the grain" so cutting across the grain gives faster moisture loss. In addition the geometry of the pieces (i.e. the chip shape) affects the way in which the pieces arrange themselves when placed into piles. This determines the ventilation and hence the rate of moisture loss from the pile. Shrinkage can occur at lower moisture contents in wood when cut mainly tangentially to the growth rings rather than along the grain. Subsequent moisture uptake can result in re-swelling.

If the drying biomass is left outside, the rain will wet the outside of the material. If stored in large piece sizes as logs or chunks with good air movement between, this will soon dry again by evaporation. Conversely, smaller piece size (e.g. when cut into chips or stored as shredded bagasse or rice husks) will result in an increased exposure of cell cavities.

6.4 Agricultural residues

Figure 6-19 Biomass has good potential to provide rural areas with a renewable source of energy

Since biomass in all its forms is widely distributed it has good potential to provide many rural areas with a renewable source of energy. The challenge is to provide the sustainable management, conversion and delivery of bioenergy to the market place in the form of modern and competitive energy services.

Agricultural crop residues often have a disposal cost associated with them. Therefore, the “waste-to-energy” conversion processes for heat and power generation, and potentially for transport fuel production, can have good economic and market potential. They have value particularly in rural community applications, and are used widely in countries such as Sweden, Denmark, Netherlands, USA, Canada, Austria and Finland.

Large quantities of crop residues are produced world-wide and are often under-utilised. These include rice husks, sugar cane fibre (bagasse), maize cobs, coconut husks (copra), coconut, groundnut and other nut shells, and cereal straw. Coconut and nut residues tend to be used only on a small scale, whereas larger quantities of rice husks, bagasse and straw can be accumulated in one place. Such wastes tend to be relatively low in moisture content (10-30% m.c. wet basis) and therefore more suited to direct combustion and gasification rather than to anaerobic digestion (which normally uses wet wastes such as tomato skins, meat cuttings or reject fruit).

Crop residues such as straw, bagasse and rice husks, if not having to be returned to the land for nutrient replenishment and soil conditioning, could be used more in the future for power generation, possibly at times in co-combustion with coal or gas and in appropriate conversion equipment with low emissions now that such technology is well proven. In Australia major residues produced include those from winter cereals, sugar cane and sorghum. Current farming practice is to plough these residues back into the soil, or they are burnt, left to decompose, or grazed by stock. A number of agricultural and biomass studies have concluded that it may be acceptable to remove and utilise a portion of the residues for energy production, hence providing large volumes of material. The costs of collection, transport and storage will need to be factored into any potential use for energy.

6.4.1 Bagasse

Bagasse is a fibrous material left after the sugarcane is crushed and the raw sugar juice is extracted at a sugar mill. Over 11 million wet tonnes of bagasse are produced annually in Australia, with a total energy content of around 120 PJ. Annual volumes vary from year to year, and are produced only during the sugarcane crushing season, which may last as little as 18 weeks between mid June and mid December. Sugar mills are generally self sufficient in energy via the combustion of bagasse for steam and electricity. At present not all bagasse is utilised for energy generation and there is potential to upgrade (at significant cost) the co-generation facilities at a number of mills. Improved steam efficiency at some mills would release more energy for electricity generation but would require capital investment.

Bagasse has considerable potential as a biomass fuel since it arises mainly at sugar factories where flows of bulky volumes of biomass in the form of sugar cane (Figure 6-20) are already well organised. Each fresh tonne of sugar cane brought into the factory for processing yields around 250kg of this residual fibre. Any country which grows sugar cane, including Australia, therefore has a significant biomass energy resource available in the form of the crop residue remaining after sugar extraction (Figure 6-21), which has been already collected and delivered to the processing plant. Most sugar mills use this bagasse as a source of heat for raising steam to process the cane juice and extract the sugar, but because the large volumes of bagasse can also create a disposal problem, they have tended to burn it inefficiently just to avoid accumulation of surplus wastes.

Figure 6-20 Sugar cane billets as delivered from the harvester then fed by belt conveyor into the sugar processing plant

Many sugar mills also generate around 2-3MW electricity from the steam for their own use but at present only a few Australian mills have installed larger boilers and steam turbines to allow the export of significant quantities of surplus power because of operational and contractual difficulties of selling the power only during the cane crushing season. The potential for a mill to generate 20 to 30MW_e all year round by using other biomass in the 6-8 month non-crushing season has created recent interest in a number of countries including Australia.

Studies conducted in Thailand, Jamaica, Brazil and Zimbabwe (*inter alia)* have shown that optimisation of bagasse combustion for energy, together with the utilisation of some of the cane trash usually left in the field after harvest (tops and leaves), or burnt off before harvest to make access easier for the machines, could provide fuel for up to 50GW of generating capacity worldwide. This is based on more than 800 sugar mills each with >5MW$_e$ capacity (of the world total number of 1670 mills) mainly situated in India, Pakistan, S.E. Asia, China, South Africa, Central America, the Caribbean, and South America. The practice of burning the crop prior to harvesting to remove the trash is declining due to environmental concerns and now around two thirds of the Australian crop is “green harvested” without burning.

Figure 6-21 Fibrous bagasse residue, after extraction of the sugar, can create a disposal problem since, unlike the sugar beet pulp in Europe, there is little demand for it as livestock fodder

In Australia there are 24 raw sugar mills and if all were upgraded to utilise the bagasse and woody biomass in the non-crushing season efficiently for cogenerating of heat and electricity, then the total plant capacity could potentially supply as much as 3,400MW$_e$ (or 3.4GW). More than 20 TWh/y of electricity could be generated, which would reduce carbon emissions by over 16MtCO$_2$ - assuming electricity from coal would be displaced. Cost analyses have shown the generating costs using modern bioenergy plant could be competitive with other renewable energy technologies under the mandatory renewable energy target legislation. However not all of the mills might be able to economically benefit due to the need to have guaranteed supplies of suitably priced biomass feed for the period each year when bagasse is not available, over the entire economic life of the project. When new generating equipment is installed at high capital cost, it is essential that the plant is fully utilised for as much of the year as possible to achieve the lowest cost electricity. With the sugar cane crushing season lasting as little as 18 weeks, this places pressure on project developers and operators to secure reliable low cost feed for some 30 weeks each year.

The link between the power industry and the sugar industry may lead to different sugar cane management practices, the need for partnerships, and possibly third party investment in capital plant. The gradual development of a number of new cogeneration plants in the Australian sugar industry over the past ten years shows that this is achievable but is a slow process.

A power generating company also has to consider the prospect that the world and Australian sugar industries are not buoyant, and a company that it partners with in a new power plant development may not survive for the time taken to recover the significant, up-front capital costs. There are risks for both the power industry and the sugar industry that need to be fully analysed when a project is being evaluated.

The flows of materials and energy in the sugar cane processing industry are worth highlighting with regard to the potential biomass supply as a co-product (Figure 6-22).

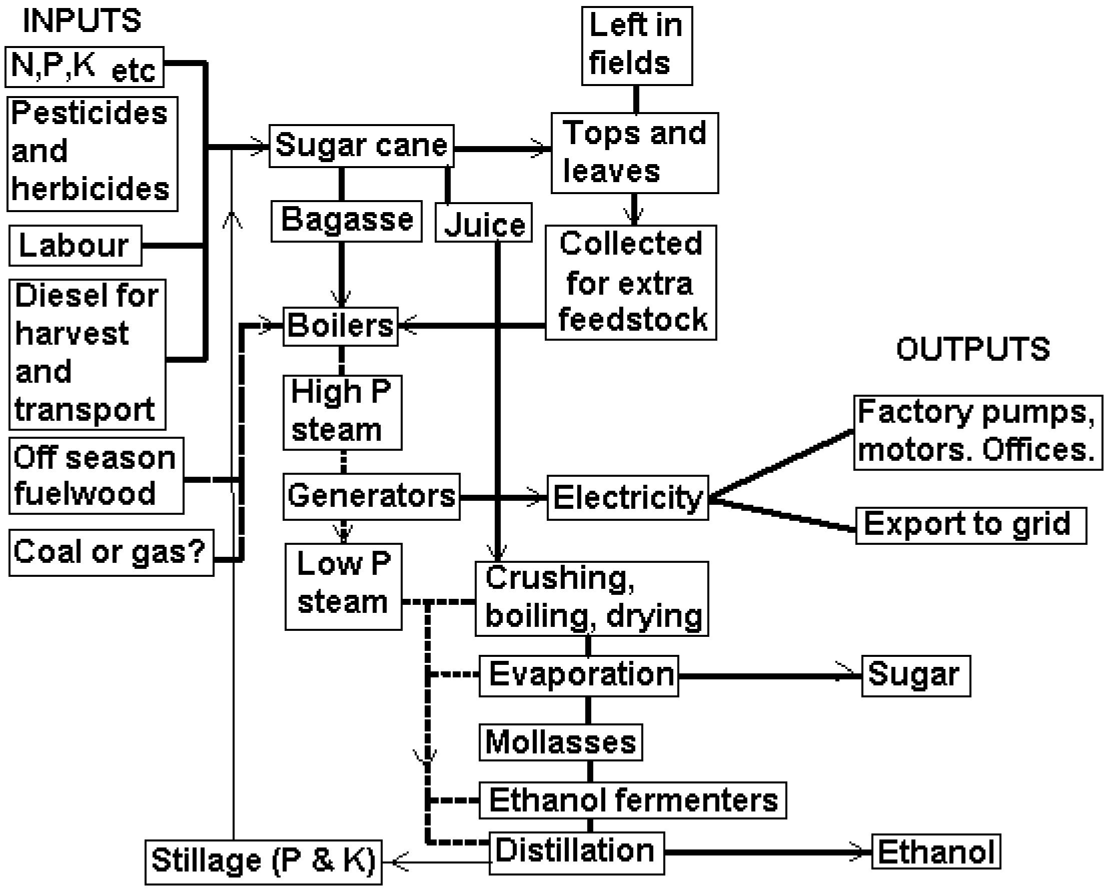


Figure 6-22 **Energy and material flows during the sugar cane production and processing operation**

Most sugar cane is grown on high rainfall coastal plains and river valleys and is an important part of the economies of these regions. Most cane farms are family owned and are between 30 and 120 ha, producing around 6,000 t/y on average. Only 2.5% of the cane is grown by sugar mill owners. Water is critical for good cane production and two thirds of cane growers have some form of irrigation. Each year over 40 Mt of harvested cane produces nearly 6Mt of raw sugar giving an average of 100t/ha of cane and 13.7 t/ha of sugar. The majority of Australian sugar is exported and is therefore subject to fluctuations in international prices.

Cane harvesting practices were developed to leave around half the biomass in the field to reduce subsequent disposal costs. If sufficient demand is created for these residues for energy purposes, then the volumes of biomass that could become available as feedstock for additional power generation for export off site could double. This assumes there is no soil nutrient deficiency risk as a result of collecting and removing this material, which also helps to retain valuable soil moisture and to suppress weed growth. Research to ascertain how much can be removed without detrimental effect is underway. But it should be noted that in the traditional harvest method of pre-burning, little trash remains. The additional revenue from electricity generation could change the agronomy of sugar cane production since both sugar and fibre yields could become equally important. High fibre cane varieties grown at high-density plantings and refining the harvesting method to integrate field trash recovery may all become commonplace to meet the demands of co-generation.

An interesting factor is that sugar cane has been grown successfully on the same land for many years, often without much crop rotation being possible due to the fixed infrastructure of light rail collection systems linking the fields and used to take the cane to the factory (Figure 6-23 and Figure 6-24). Queensland sugar mills own, operate and maintain 4,100 km of narrow gauge (610mm) railway, used to deliver the cane to the mills. In some regions, including northern NSW where light rail is uneconomic due to the cane fields being less concentrated, bins designed to be easily loaded on to trucks are filled by the harvester in the field and then used for transporting the cane to the plant.

Figure 6-23 Transport of sugar cane from field to factory by small rail and bins representing a well-developed biomass transport process

Sugar cane is a C4 plant, as is sorghum, meaning they have a better photosynthetic efficiency and hence ability to convert carbon dioxide using sunlight than do other more common C3 plants. It also usually requires only minimum inputs of pesticides and herbicides compared with growing cereal and other crops. Whether it can be considered as grown on a truly sustainable basis is debatable, as some nutrients such as N need to be added in the form of fertiliser to replace those removed in the crop. However if the stillage or effluent from the crushing and distillation process (during ethanol production) and the ash from combustion of the bagasse were to be returned to the fields, (particularly where the cane trash was also removed for energy purposes), then only N would be in deficit.

There is some evidence that excessive use of water and fertilisers to sugar cane in some areas of Queensland is contributing to environmental problems such as damage to the Great Barrier Reef. If sugar cane is to be used extensively for energy purposes, research is needed into new practices including new varieties to extend the season, organic production using minimal agri-chemicals, and increased crop rotation using other plants that can also be used for fuel in the non-cane crushing season.

Mill throughputs range from more than 3 Mt to less than 500,000 t of cane per year, depending on the size of the mill. Increased crushing rates provide greater economies of scale. Generating renewable electricity for export from the surplus biomass might assist the long-term economic sustainability of the sugar industry.

The Rocky Point co-generation project was one of the first of a series of sugar industry cogeneration developments. Another similar project at Broadwater sugar mill has taken almost 10 years to develop[3]. Other plants are under development or being evaluated and several research projects are

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[3] Moller D. (2010). Implementation issues in the first 10 years of a bioenergy project. Proc., Bioenergy Australia, 2010 Conference “Biomass for a clean energy future”. Sydney, 8-10 December. www.bioenergyaustralia.org

underway to improve the use of bagasse as fuel, such as reducing the moisture content of bagasse leaving the milling process. This could lead to technology for improving the energy balances of bagasse utilisation for a significant portion of the Australian sugar industry.

Figure 6-24 Rail bins being filled in the field by the harvester support trailer

6.4.2 Cereal straw

Cereal crops such as wheat produce around 2.5 – 5 t/ha of straw depending on crop type, variety and the growing season. Maize stover can be higher yielding. Crop residues range from 10-40% moisture content (wet basis), giving a typical heating value of 10-16MJ/kg wet weight.

In terms of comparative gross energy values, 1 tonne of straw equates to approximately 0.5 tonne of coal or 0.3 tonne of oil. It has higher silica content than other forms of biomass, leading to ash contents of up to 10% by weight.

After harvesting of the grain the straw is often burnt in the field (Figure 6-25) as there is only a limited demand for it for animal bedding, stock feed, mushroom compost or garden mulch. Burning is a cheap method of disposal and can help to reduce the incidence of disease carry-over to future crops. However this practice is now banned in European countries for air pollution reasons and risks of road accidents from drifting smoke. This has led to higher disposal costs by having to bale and remove it or to incorporate it back into the soil by chopping and additional cultivation operations. Many long term evaluations show that there is little benefit to the soil or its organic matter content from such incorporation practices as the straw consists mainly of cellulose and with very low C:N ratios; so it returns limited nutrients to the soil. Hence the utilisation of straw for energy purposes has increased in Europe. Denmark leads the world with thousands of straw burning facilities providing district heating (3-5MW), industrial process (1-2MW), and domestic heating (10-100kW) per Figure 6-26. The straw is normally stored on the farms, only being delivered to the central heating plants as needed. Used on farm at the small scale in Europe, it can be utilised for grain drying or heating animal houses as well as to supply the farmhouses with space and water heating[4].

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[4] A study in 2003 of the “potential for energy from agricultural wastes in NSW” was undertaken by the Sustainable Energy Development Authority, since disestablished.

Figure 6-25 Open air burning of straw as a disposal method causes air pollution (and also the waste of a potential biomass resource)

If the straw remaining in the field is assumed to have zero economic value, and with the costs of collection at around $50/t for raking, baling etc., then the stored energy in the straw, usually as large round or square bales, would cost around $4/GJ assuming a moisture content of 15% wet basis. Cartage to a central conversion plant site might add another $6-10/GJ if within 25 kms on average, leading to a high electricity generating cost of around 15-20c/kWh. This may be an economic option in Denmark and elsewhere due to their high power prices, heating requirements and various forms of subsidy, but is unlikely to be the case in most other cereal growing countries such as Australia when compared with generation costs as low as 7c/kWh for wind power and 3c/kWh or less for power from large coal-fired stations. Direct combustion of the straw for process heat in nearby plants (such as in malting barley factories for breweries) may be more economic, but in many places unlikely to compete with coal or natural gas.

Part of the reason for the relatively high cost of straw is that it is not normally delivered to the processing plant as part of the cereal harvesting process as is the case for sugar cane bagasse. Additional collection, transport and handling operations are required. Although straw has a relatively high energy density (MJ/kg) for biomass due to its low moisture content, even when baled it has a low mass density. So the energy density per truckload is 10 to 20 times less than that of coal or oil, and reaching the maximum truck payload is unlikely.

Conversion equipment, whether for heat and/or electricity, is also more expensive than for the same output capacity when using fossil fuels ($/kW), since larger plant and more complex conveying equipment is needed. To keep transport costs down the plant may have to be limited to around 2-3MW, which means it is not possible to achieve economies of scale.

The development of a range of straw pellets and briquettes sized at up to 300 mm by 75 mm (Figure 6-27) and with a greater mass density than bales has occurred in an attempt to try and reduce transport costs and also enable automatic feeding to occur, particularly at the smaller domestic scale (10-30kW heat output). Specialist pellet burners are available on the European market and are suitable for wood or straw pellets, but the cost of the total system is relatively high. The big advantage is that the pellets can be delivered in bulk by small truck to the dwelling or small business as required, and fed automatically just like heating oil.

An example of one of many models of straw-fired burners as installed in Danish farms for heating the dwelling and animal houses. Note the door for ash removal.

Figure 6-26 A straw-fired burner for heating Danish farm dwelling

Figure 6-27 A range of commercially produced straw pellets and briquettes

6.4.3 Rice husks

Rice husks are an abundant agricultural residue, making up 20-25% of the harvested rice grains on a weight basis and separated out at the processing centre. Indonesia alone produces around 8Mt per year. The husks have a high silica content, which can cause an ash problems and possible fouling within the boiler on combustion, but their homogeneous nature lends them to technologies such as gasification, requiring a uniform fuel quality for best results. Several commercial rice husk gasification plants have operated for a number of years to supply heat in SE Asia and Australia.

6.5 Energy crops

Figure 6-28 Oilseed rape crop for biodiesel growing in Manawatu, New Zealand

Growing crops for fuel versus food, feed and fibre, is under close scrutiny (see chapters 4 and 12). A number of annual and perennial species have been identified as having high efficiency when converting solar energy into stored biomass, which can then be converted into heat, electricity or transport fuels with low overall carbon emissions. High yielding, short cycle crop or C4 plants (e.g., sugar cane and sorghum) can give stored energy equivalents of over 400 GJ/ha/y at the commercial scale, leading to very positive input/output energy balances for the overall system, provided significant amounts of fossil fuel are not used in processing operations (for example use of coal as an energy supply to some corn-ethanol distilleries in the USA).

The relatively low energy yields per hectare for many oil crops (around 60 to 80 GJ/ha/y for oil) compared with crops grown for cellulose or starch/sugar (200 – 300 GJ/ha/y), has led the US National Research Council advising against any further research investment in this area. However, most liquid biofuels, when substituted for fossil fuels, will help reduce CO_2 emissions[5]. Therefore, a combination of bioenergy production with carbon sink options can result in maximum benefit from mitigation strategies. This can be achieved by planting energy crops such as miscanthus or reed canary grass into arable or pastureland, which in some circumstances can also increase the carbon density of that land, while also yielding a source of biomass. Utilising the accumulated carbon in the biofuels for energy purposes, and hence recycling it, alleviates the critical issue of maintaining the biotic carbon stocks over time, as is the case for a forest sink. Increased levels of soil carbon may also result from growing perennial energy crops, but detailed life cycle assessments are required for specific crops and regions. Correct species selection to meet specific soil and climatic site conditions is necessary in order to maximise yields in terms of MJ/ha/y.

There are many agricultural food crops that can be grown as energy sources, including sugar cane, corn (maize), wheat, sorghum, and vegetable oil-bearing crops such as sunflowers, rapeseed (canola), and soya beans. The majority of these crops are grown as liquid fuel feedstock, that is they are harvested and processed into biofuels such as ethanol or biodiesel. With the exception of sugarcane ethanol, most need government support to compete with petroleum products derived from crude oil at below around US$ 100 per barrel. The most widely grown energy crops are sugar cane

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[5] IEA, 2008. From 1st to 2nd generation biofuels technologies, http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=2079

(there is even a special high fibre species known as 'energy cane'), particularly in Brazil, where over 6 million flex-fuel vehicles have been run on 85% ethanol fuels. There is also large-scale use of maize for ethanol in the USA and, to a lesser degree, oilseed rape and other vegetable oils for biodiesel in Europe where the production of liquid biofuels is subsidised. Currently in many countries including Australia, relatively few agricultural crops are grown specifically as energy sources because it has been uneconomic to do so. However there is continued interest in ethanol and biodiesel (Figure 6-28) as well as the longer term potential for algae.

Benefits associated with biodiesel, compared with mineral diesel, include a reduction in greenhouse gases up to 80%, almost complete reduction of sulphur oxide emissions, a 40% reduction in particulate matter, high biodegradability, and enhanced energy supply security. There are currently some 85 biodiesel plants around the world, although several have recently closed down in Germany after the excise tax exemption support scheme was removed. The cost of the raw material is the most important factor affecting the overall cost of production. Energy content is similar to diesel (Table 6-2).

Crops grown specifically for energy supply purposes have less immediate potential for use for energy than existing crop residues because of the higher delivered costs in terms of $/GJ of available energy. Also land used specifically for biomass production will generally have an opportunity cost attributed to it for the production of food or fibre, with this value being a valid inclusion in economic analyses.

There have been calculations made to indicate that globally there is enough land available to provide the world's population with all its needs for food, fibre and energy. (Equitable distribution of these basic necessities is another issue that is yet to be resolved). Integrating crop production with all three products is the challenge. Oilseed rape (canola) for example produces oil which can be used for cooking or energy, an edible high protein meal, and straw which can be used as a paper pulp or combusted.

Table 6-2 Typical lower heating values for some vegetable oils & diesel, though these all vary with source

Oil source	Energy content (GJ/t)
Canola	40.4
Safflower	39.7
Sunflower	39.7
Diesel	38.5

A future for "Designer Biomass" by developing suitable genetically modified crops cannot be ignored. Certainly the concerns over genetically modified organisms entering the food chain without full and proper evaluation are of considerable concern. However the technology is here to stay and does have great potential. Imagine having several attractive C4 plants which have nitrogen fixing ability, consume relatively little water, are high yielding, easy to harvest and can be grown extensively to produce protein, carbohydrates, fibres and lignin which can all be processed through a "biorefinery" into a range of industrial, edible and energy products. The issues of sustainable production, lack of biodiversity and monocultures would need to be carefully considered. But with some innovative thinking we could be doing things a lot better than we do now in traditional agriculture.

7. Delivered cost of biomass

7.1 Summary

The cost of biomass (production, harvesting and transport) is a key determinant of the viability of bioenergy projects. International experience has shown that the biomass fuel procurement cost can account for some 50-60 percent of the total bioenergy costs. Of the total delivered fuel cost, biomass production typically accounts for 25 percent, harvesting 50 percent and transport to the power plant 25 percent.

In Australia, biomass from short cycle tree crops is yet to be commercially developed, although more than 12,000 ha of mallee trees have been planted in Western Australia. The opportunities for this new biomass source are covered elsewhere in this report. This chapter considers international experience and study methodologies that analyse different biomass delivery systems and their costs for both small and large-scale operations, noting regional differences including local growing conditions and energy and labour costs.

Two overseas case studies are presented here to assess biomass delivery logistics and their costs and determinants. While not directly related to Australian crops, these studies provide useful methodologies for assessing the optimal delivery system and associated delivered fuel cost. They also highlight the significant variability in cost outcomes achieved by the selection of different delivery systems. Detailed analysis of specific feeds in Australia is therefore useful (see Chapters 9,10 and 11).

The first case study uses a computer simulation to analyse, and hence minimise, the delivered cost of woody biomass from local plantation forests to an energy plant in the Nelson area of New Zealand. The average transport distance is 80 kilometres and the forest owner is paid NZ $20/t for the forestry residues. Seven different systems for transporting and handling the biomass were analysed and compared, taking into account constraints such as maximum legal payloads on local highways (23 tonnes). This case study illustrates that there are significant cost variations between various systems resulting in delivered costs ranging between NZ $2.3/GJ and NZ $5.7/GJ. A major part of the delivered cost is in handling and transport, which could be reduced by increasing operating efficiencies and maximising truck payloads.

The second case study relates mainly to short rotation coppice willow in the UK. Although this is not a favoured species for Australia, considerable research has been undertaken on this energy crop in Europe and it provides a comprehensive methodology applicable to both agricultural residues such as cereal straw and short cycle forest crops. Eight different systems and the delivered costs to the power plant were compared for both a large-scale operation (supplying a 10 MWe biomass power station) and a small, on-farm scale operation (to supply a 400 kW heating or co-generation plant). The lowest delivered fuel costs were achieved with the two options that avoided intermediate storage by delivering fuel directly to the power plants.

These studies revealed that the cost of delivered biomass is very project specific, with the main cost determinants being source and type of biomass, fuel feedstock production costs, harvesting costs, transport distances, fuel moisture content, fuel quality (with penalties for contamination), capital costs of handling equipment, and labour requirements.

The UK study involved considerable stakeholder involvement and aimed to bring together all the relevant information, synthesise it, and then present a series of options for industry to determine the optimum harvesting and processing systems. Various concepts and scale of operation were investigated. These included large-scale cut and chip, large-scale cut and billet, and smaller-scale stick harvesters for both the power plant and the on-farm co-generation plant. For the large plant the study also examined the interaction between fuel drying and the form of the delivered biomass.

Using a one-pass cut-and-bale machine for felling and baling coppiced material was identified as having advantages. Although such a machine does not currently exist commercially, it was included in the studies as a potential concept for assessment and possible development. The lowest cost option was using a Claas forage harvester with no intermediate storage and year-round harvesting. Key study recommendations were to:

- bale the cut short cycle crop sticks or chunks into large round or square bales using existing agricultural baling machines mounted on a tractor/mower, to give a one-pass machine, with either:
    - bales dropped on ground for subsequent collection by tractor/front loader and transport to trailer or truck
    - or bales carried to headland on baler for later collection by truck.
- Develop a billet system around the Austoft sugar cane harvester or a chain cutter/stick harvester with a billeter mounted on the chassis. Either would need a conveyor with support trailer running alongside, or a mounted bin to carry billets to the end of the row for unloading hydraulically.
- For small-scale systems on farms with existing grain drying facilities, a manual chainsaw or simple tractor mounted single disc saw blade used for older single stem trees and the trees later manually fed into a mobile chipper.

Table 7-1 Indicative costs for supplying biomass to a plant up to 100 km distance

Wood process residues, bagasse etc used on site	$0 - 0.20/GJ (or even negative if disposal costs are avoided)
Forest arisings from the landing or collected from the cutover	$2.00 – 3.20/GJ
Short cycle crops (such as oil mallee)	$4.20 – 6.30/GJ
Crop residues – baled and carted	$4.80 - 8.00/GJ

7.2 Introduction

Harvesting is a considerable cost in the production of biomass, with production often accounting for 25% of the total delivered fuel costs, transport 25% and harvesting 50%. Overall the harvesting and transport operations when producing energy crops (including SCC) can account for 50-60% of the total bioenergy production costs.

Tending and harvesting operations associated with growing energy tree crops on short cycles in many countries are generally labour intensive. Machinery required to automate forestry harvesting systems is large and expensive, resulting in manual labour being cost effective and consequently little money being invested in the development of new machinery. However, the cost of employing manual labour is increasing due to higher wages and associated costs (including increased insurance rates for high risk forestry operations). At the same time mechanised forestry equipment and its associated technology is becoming cheaper and more readily available increasing the availability and suitability of a range of machines.

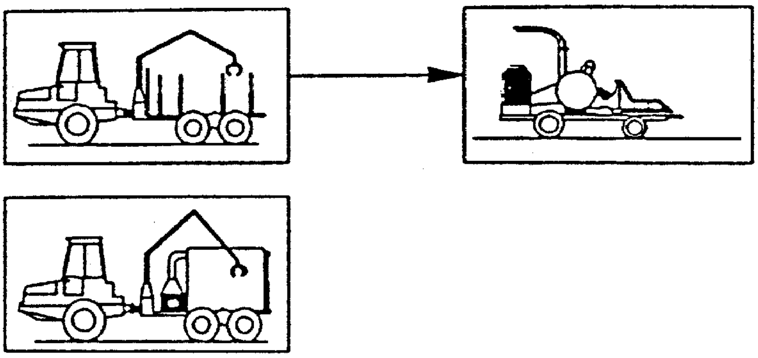
Harvesting costs are influenced by yield, tree size, stocking density, the volume removed from a given area (which will affect the cost of felling and extraction) and the mean annual increment (MAI). These variables will also influence the supply zone radius required and therefore the haulage costs to meet a given demand.

7.3 System options

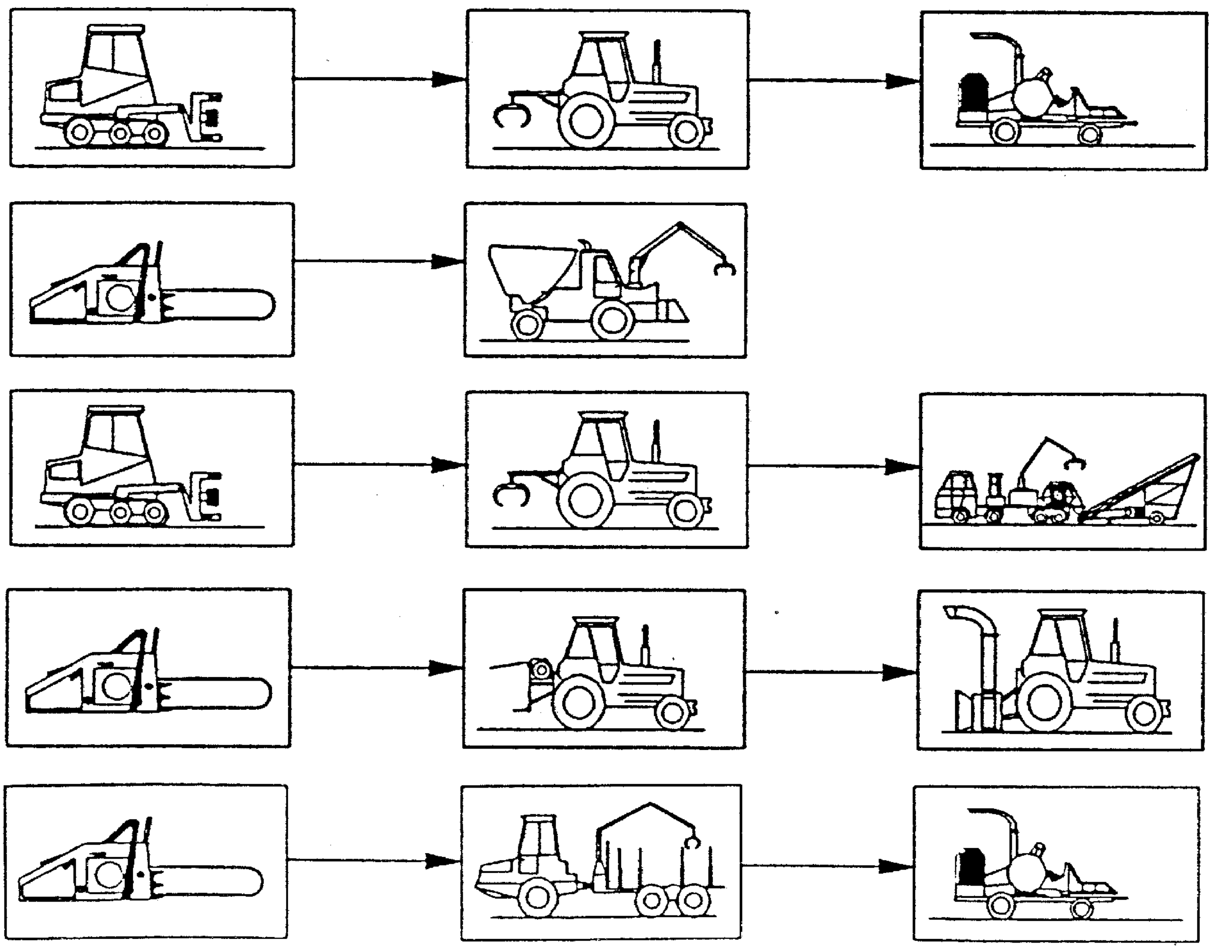
7.3.1 Harvest, collect and process

A large number of systems are feasible for harvesting, collecting and processing biomass with the intent to use all or part of the material for energy purposes. Several examples are shown below, based on forest arisings as an example and using the symbols defined earlier to depict the machines involved. To be most effective in terms of fuelwood delivered to the power plant at the lowest cost, the productivities of the various machines in terms of tonnes per hour need to match each other to avoid expensive delays and down time.

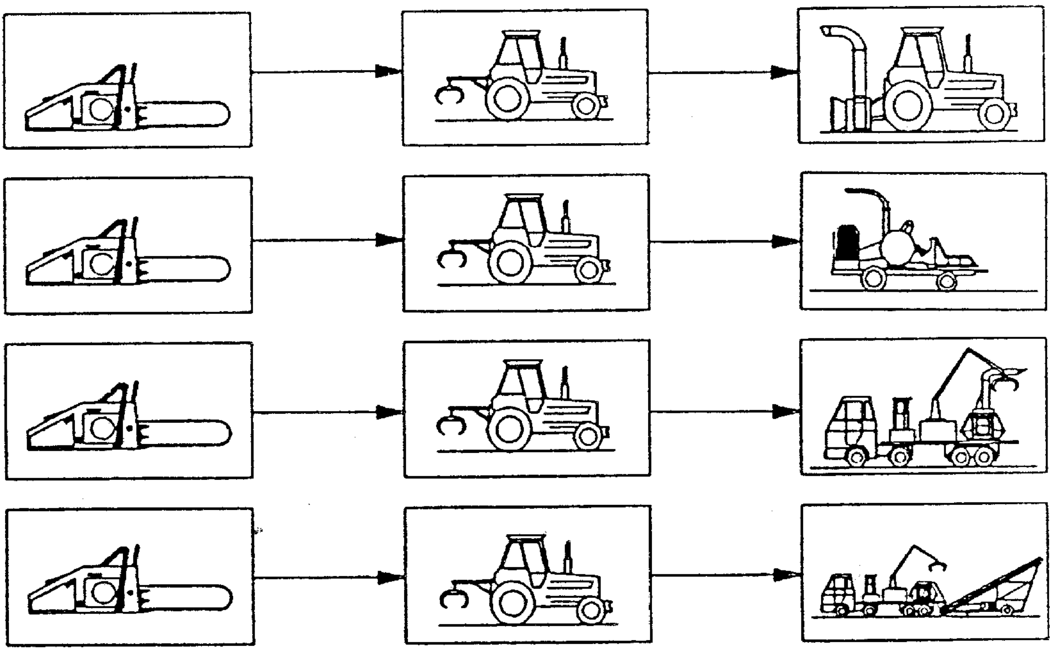
(i) Two systems of harvesting of arisings from the forest cutover



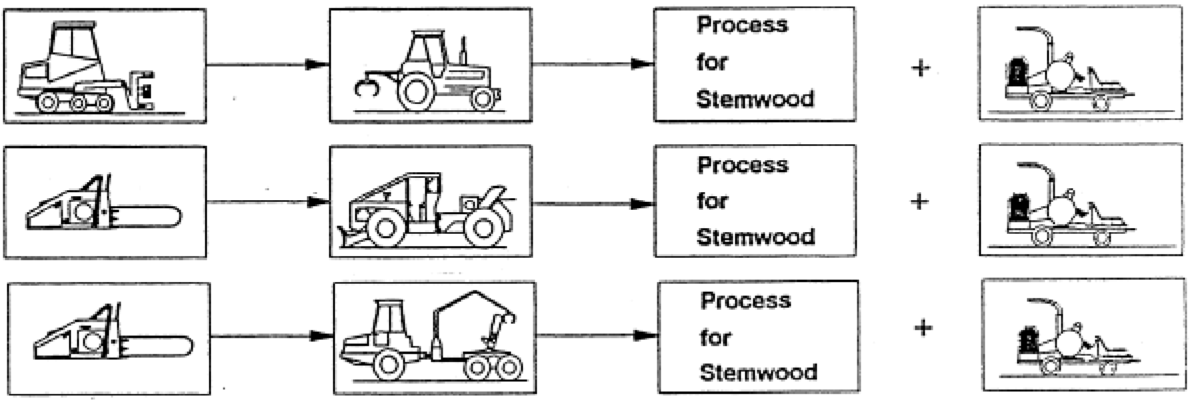
(ii) Five whole tree harvest and extraction options for comminution at the landing or in the forest using a mobile chipper or chipper forwarder



(iii) Four whole tree harvest, extraction and comminution options more suited to forest thinnings and selective harvesting.



(iv) Three integrated harvesting options for processing trees for logs and timber products with the forest residues chipped for biomass.



7.3.2 The overall biomass supply system

This following sections describes a computer model designed (independently of this project) to analyse and hence minimise the delivered costs of biomass by optimising the system components for any given site. Woody biomass is used as an example, though the model can also be used for cereal straw, etc.

Most forms of dry biomass can be handled in a number of ways. For example cereal straw can be handled loose, chopped, baled or briquetted. The chosen method depends on the material, its moisture content, the transport distances involved, the storage method, the storage period, and the scale and type of conversion plant. Selecting the components of the overall system to minimise the total delivered fuel costs is a complex process. Poor selection can lead to more expensive fuel.

7.4 Case study 1 – Assessment of delivered forest arising costs – New Zealand

A number of supply scenarios were considered to provide indicative overall costs and the various cost components when delivering biomass from forest residues (or “arisings”) to an energy plant in the Nelson region of New Zealand. The values shown in the graph (Figure 7-1) are in $NZ (NZ$ 1 = A$ 0.8 approx.). It was assumed that the residues were sourced from forests within the Nelson region with an average transport distance of 80km to an energy conversion plant located in Nelson city. The price paid to the forest owner for the residues was $20/t.

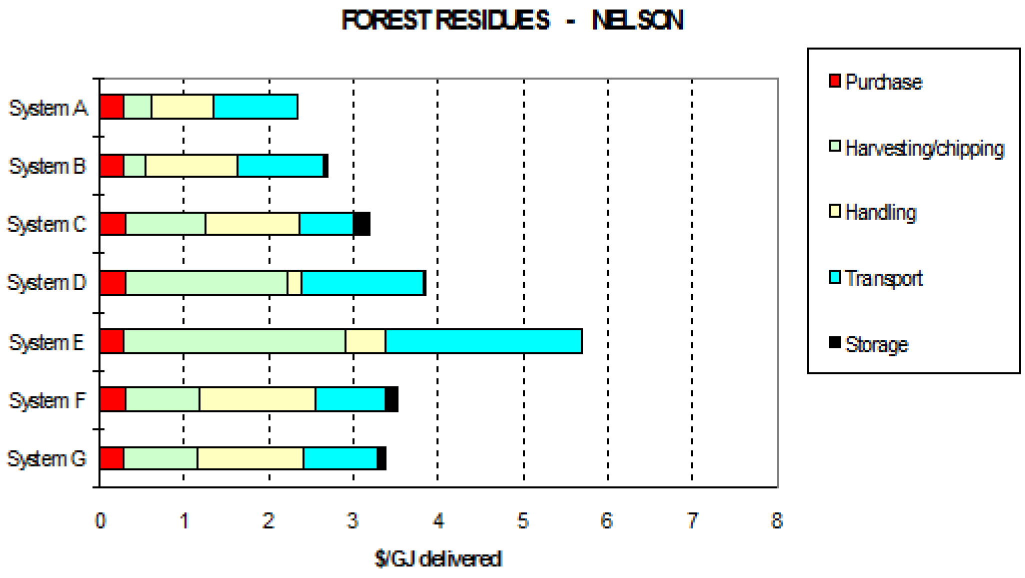


Figure 7-1 Costs of delivered fuel from forest arisings, from eight different systems (NZ$)

Systems of transport and handling:

A **_Landing residues only_**: load onto on-highway truck; transport to energy plant; unload and chip.

B **_Cutover residues_**: forwarder to landing; load onto on-highway truck; transport to energy plant; unload and chip.

C **_Landing residues_**: load onto off-highway truck; transport to central processing yard in forest (5km or less); unload, chip with mobile chipper direct into on-highway truck; transport to energy plant.

D **_Cutover residues_**: chipper forwarder; transport to stockpile (10% fibre loss); front-end loader to load on-highway truck; transport to energy plant.

E **_Cutover residues_**: chipper forwarder and transport to landing; transfer into set-out bins; collect bins with hook truck transport to energy plant .

F **_Cutover residues_**: forwarder to roadside; stockpile *(indefinite storage);* chip using mobile chipper; stockpile (10% dry matter fibre loss); front -end loader to on-highway truck; transport to energy plant.

G **_Cutover residues_**: forwarder to roadside; stockpile; chip using mobile chipper into on-highway trucks; transport to energy plant.

The computer model used was very detailed, allowing for travel distances over a series of road types (tracks, B roads, A roads, motorways etc) as occurs in practice. It even accounts for the time taken, and hence cost, to cover a truck load of chips with a tarpaulin. The main assumptions used to provide detailed data for the transport model in this study included the following:

The harvest and process machines used in these systems were:
- 20 tonne excavator-based grapple loader.
- mid-sized, rubber-tyred, front-end loader with hi-lift bucket for top loading chip trucks.
- electric/hydraulic knuckle-boom unloader at conversion plant.
- Morbark EZ 30 mobile drum chipper, trailer mounted.
- Bruks electric powered drum chipper (70cm), fixed installation.
- Kockums/Bruks chipper forwarder.
- 15 tonne forwarder with modified load space.

The costs of each machine were calculated using the following common assumptions:
- all in-forest equipment working one shift/day.
- 235 working days per year.
- all equipment at plant working two shifts per day.
- discount rate 9%.

The on-highway truck had a maximum legal payload of 23 tonne and the off-highway truck used only on private forest roads had a 40 tonne payload.

There were significant cost variations between systems (Figure 7-1), resulting in delivered costs ranging between NZ$5.7/GJ and NZ$2.3/GJ. The results also showed a major part of the delivered cost was in handling and transport, which could be reduced by increasing operating efficiencies and ensuring truck payloads are maximised.

7.5 Case study 2 – Assessment of delivered willow SCC biomass costs - UK

Although willow is not the first choice of energy crop in Australia, it is the preferred species in Northern Europe and more research has probably been undertaken on it than on any other energy crop. The reason it is included here is that the principles used in the methodology also relate to agricultural residues and other short cycle crops.

In order to produce a high quality biomass fuel on a sustainable basis and to minimise the delivered costs, the whole process needs to be viewed as a system. The harvested crop can be quantified in terms of GJ/ha/year, but losses during the harvest, storage and transport operations will reduce the energy available for conversion to heat and power. Minimising these losses needs to be given due consideration during the development of the optimum system.

In the assessment of harvesting options for willow in northern Europe, it was assumed there is only a short harvest window in the winter period, but that the fuel will be required constantly at the energy plant over a 12-month period. If electricity production is the main objective, then a 10 to 12 month storage period is inevitable in order provide constant feed that will maximise return on investment in the generation plant. All-year-round harvesting could serve to partly overcome storage and drying problems but, although worthy of further investigation, was not considered in this study.

7.5.1 Concepts and scale of operation

A number of broad harvesting categories can be identified, based partly on the scale of operation:

1. Large scale cut and chip, self-propelled machine. Chips stored on farm or at conversion plant.
2. Large scale cut and billet, self-propelled machine. Billets transferred to simple on farm storage initially (Figure 7-2) then later comminuted to the form required at the conversion plant.
3. Large-scale stick harvesters, self-propelled machine. Where no indoor storage facilities exist for large volumes of material, which is the case on many farms, sticks can be stored outside in piles, in tied bundles or as compressed bales. Comminution to produce the biomass in a form suited to feeding into the conversion plant could then be undertaken later, either on the farm if for local use or to maximise transport payloads, or at the power station.
4. Medium scale machines mounted around conventional self-propelled power units for stick, chip, billet or bale production as above.
5. Small scale, trailed, stick harvester for grower / contractor use on smaller areas using conventional agricultural tractors as power units (Figure 7-3).

Figure 7-2 **Billets of willow stock-piled on farm ready for later comminution or transport to power plant**

Figure 7-3 **Tractor-powered stick harvester suitable for small scale harvesting**

Depending on the scale, comminution can be accomplished:

- on the farm if the fuelwood is destined for local use
- on the farm in order to maximise transport payloads
- at the power station if it is cheaper overall to do so and also to provide a consistent fuel quality to suit the conversion plant design in terms of piece size and moisture content.

Until the market for fuelwood from SCC willow develops there will be only a limited demand for harvesting equipment. Therefore it would be impractical and not economically viable for a business to consider manufacturing harvesting equipment to suit all the above categories. In this case study only the two categories were considered:

1. A large scale system to supply a 10 MWe power generation plant by harvesting at least 1,000ha of SCC per year

2. A small scale system to supply the grower with sufficient fuelwood to be used on site for heating alone or possibly for co-generation with grid connection to export excess power.

7.5.2 Assessment of SCC harvesting and fuel supply system costs

Project reports on SCC harvesting and drying were reviewed and a summary table of all characteristics of the harvesters that had been tested and evaluated in the field was compiled.

Informal discussions were held with a wide range of stakeholders in the industry both in the UK and Europe to ascertain their personal concepts for harvesting SCC and priorities for Research and Development. There was no obvious consensus and many personal preferences were evident. So no opportunity resulted to “pick a winner” from all the harvesting options presented.

Design variables were developed for a SCC harvester. For each specification parameter (i.e. overall machine size and design, work capacity, width of cut, cutting mechanism, comminution, transfer mechanism, transport from field, road transport, storage, drying) its effect on the other variables, the limitations imposed by other factors, and a list of options was produced. This summary clearly identified the fairly complex inter-dependencies of any one factor on the others.

A simple computer spreadsheet was developed to calculate storage and transport volumes for baled SCC. A method of comparing the selected systems in broad general terms based on a rating of ten characteristics was also developed. Bales and billets showed a slight overall advantage over chips, with sticks and single stem harvesting of older trees least favoured at the larger scale, but with some potential for the small scale grower/user.

Finally a meeting was held with biomass industry representatives and growers to discuss harvester options. Some general comments have already been presented above but others received are summarised below.

As a result of this overall process, the preferred concepts for harvesting machines and developing new handling and transport fuel supply systems were identified.

7.5.3 Assumptions

The standing crop to be harvested and processed was two year old willow coppice, yielding 40 green t/ha in a 12 ha field. The harvesting and various supply chain systems were modelled for power station supply from the standing crop through to the power station gate, 39.5 km away from the farm gate. Additional costs for loading and chipping / shredding at the power station were included as a separate cost. In the analysis, the costs presented are for oven dry tonnes (odt) of dry matter delivered to the power station. In the base case, the cost the growers are paid for the standing crop was taken as £20/odt (approx A$32/odt in March 2011).

The different harvesting systems result in the biomass being delivered in different forms: as bales, billets, or chips, and as green or partly air-dried material. An allowance for dry matter losses in store was made with assumptions of 4% per month loss for chips, 2% for bales and for sticks and 1.5% for billets. The user must decide what value should be put on biomass materials and dry matter losses in each different form to suit the specific case.

The scenarios listed below have been chosen to represent various practical options. The cut and chip harvesters and the Empire 2000 stick harvester have been evaluated in field trials and the performance data is based on these results. (The assumptions for capital cost, work rate etc. for each harvester machine used in the model are listed in Table 7-2.)

There is interest in the use of a one-pass cut-and-bale machine for felling and baling coppice material in the field (see Recommendation 1 below). No such machine yet exists so, in order to model this option, three scenarios were presented (A, B, C below) based on experience from straw baling, one for round bales and two for large square bales. These scenarios illustrate what might be achievable if such a machine were to be built. The concept would be a cutting-head attached to the front of a commercial baler such as the Claas Rollant or the Hesston square baler, with the cut sticks being possibly crimped or billeted before being fed into the baler directly. Dropping the cut sticks onto the ground for subsequent collection, possibly after a period to allow some drying to occur, would have some advantages but would be difficult to achieve without high field losses and damage to the stools by the baler pick-up.

Table 7-2 Key assumptions of machine costs and performance rates used in the base case models

System	A	B	C	D	E	F	G	H
	Mower /round baler (farm store)	Mower /square baler (direct deliver)	Mower /square baler (farm store)	Claas harvester (chip & farm store)	Class Harvester (direct and store at plant)	Empire 2000 (stick, farm store & chip)	Austoft Harvester (chip & farm store)	Austoft Harvester (billet & farm store)
Machine cost (£k)	?	?	?	182	182	91	190	190
Hourly harvester cost (£/h)	36.51	78.38	78.38	65.12	65.12	44.75	82.81	80.00
Work rate (odt/h)	10	16	16	10	10	7	10	10
Road transport payloads (odt)	11.25	12.0	12.0	14.85	14.85	8.7 for sticks 14.68 chips	14.85	13.5
Total loss during storage (%odt)	12	2	12	24	0	9	24	9

Note the dry matter losses during storage vary with time but for the same period (e.g. 6 months on average) are greater for chips, than for bales, than for billets or sticks. Where the biomass is taken directly to the power plant for immediate use the losses are negligible.

7.5.4 System descriptions as used in the model

(i) Large round bales

Based on the Claas Rollant baler with options for net wrapping or twine - the former being faster. (A summary of the assumptions used is given in Table 7-2). The scenario is based on the performance of a round baler for straw with some account taken of the trials on forestry residue bales using the Swedish 'bala press'. The steps involved in the supply chain are similar to those outlined for well established straw baling and handling systems. Mowing was assumed to cost £36/ha (~ A$58/ha) with the mower attached to the baler and a simple crimping or billeting system installed before the baling section. From the 12 ha area used in the analysis, 960 bales of 500kg each can be produced. The bales are dropped in the field for later collection by loader on to a flatbed trailer for delivery to the headland or farm store. A six months average store period was assumed and then the bales are collected and transported by a heavy goods vehicle (HGV) (Figure 7-4). Alternative options would be for the baler to carry the bales directly to the headland for stacking and intermediate storage, assuming the HGV could gain access to this point, or for a loader to transfer the bales from field to headland one bale at a time. The HGV is unloaded using a front loader at the power plant (Figure 5-7) and the bales are then fed into the boiler directly (Figure 7-5).

In this and all other system scenarios (except B and E which are transported directly to the power plant), the transport distance assumptions were:

Travel in field	0.5 km	(8km/h average)
Travel on farm track to farm store	0.5 km	(10km/h average)
Travel from farm store on farm track	0.5 km	(10km/h average)
Travel on unclassified roads	9.5 km	(40km/h average)
Travel on single carriageway A/B roads	30 km	(55km/h average)
Total travel distance one-way	41 km	

Figure 7-4 Transport of round bales on heavy goods vehicle and trailer

Figure 7-5 Round bales fed into shredder on automatic conveyor to feed straw burner, 24 hours a day and unattended

(ii) Large square bales direct to power plant

This scenario is based on a Hesston high density baler, which is widely used for handling straw in Danish power plants (Figure 7-6) and for industrial applications in the UK. It is assumed that these bales are bound with twine. The steps involved in the supply chain are those broadly used for straw baling systems, except it was felt that a self-loading bale carrier would not work satisfactorily amongst coppice stools. So the modified system is:

- mowing, here using a Claas header or similar, attached to the baler
- baling, directly after mowing without dropping the cut material
- Fastrac tractor and loader to take single bales from the field 0.5 km direct to the HGV
- 35t gross HGV travels 1km on farm tracks at 10km/h average, 9.5km on unclassified roads at 40km/h, and 30 km on single lane A/B roads to the power plant at 55 km/h
- unloading by front loader
- 600 square bales were produced from the 12 ha field, each weighing 800kg.

Figure 7-6 Straw bale being dropped into shredder to feed combustion plant

(iii) Large square bales to farm store

As for system B above but with a front loader and tractor/trailer to transport the bales from the field to the farm store, since it was assumed a self-loading bale carrier would not work. Unloading at the farm store and collection by HGV, after an average period of 6 months. The HGV is a 35t gross articulated low-bodied flatbed trailer, which is loaded and unloaded by a front end loader.

(iv) Claas forage harvester (cut-and-chip)

Short rotation coppice material is cut and then chipped involving the following steps :

- direct cut and chip blowing into one of two 15 m3 trailers pulled by 85 kW tractors
- in-field transport tipped at intermediate store
- pushed into a heap on hard standing by loader and stored for 6 months on average
- loader used to fill 38t articulated bulk tipping HGV
- HGV takes chipped biomass to power plant where it is tipped

Based on Forestry Commission (UK) trials, a harvesting rate of 10 odt/h was assumed, which is equivalent to 0.5ha/h. Two tractor/trailers were used to convey the chips 1 km on average to the farm store for later collection.

(v) Claas forage harvester with no storage

This uses the same harvesting machine as system D however, instead of an intermediate storage step, the material goes straight from the field to the plant using three 45m^3 trailers to collect the material direct from the harvester in the field. This illustrates a harvesting operation suitable for dry soils in fields within a reasonable transport distance (40 km) of the plant. It would be the most probable scenario if year round harvesting was proven to be feasible. Wet chips at around 50% moisture content (wet basis) are delivered.

The steps involved are:

- direct cut and chip blowing into trailers.
- in-field transport and road transport in trailers pulled by a Fastrac tractor then tipped at the plant.

As for other systems the transport scenario was:

In field	0.5 km
Farm track	1.0 km
Unclassified roads	9.5 km
A/B roads	30.0 km

The 480t of chips delivered would require a storage area of 125m long, 7m wide (for which land rent is included in the analysis) and be piled 3m high.

(vi) Empire 2000 stick harvester

(Figure 7-7) The costs/ hour and work rates for this system were taken from UK Forestry Commission calculations. The steps are:

- sticks cut and carted to the headland by the harvester.
- loader loads trailer and tractor.
- on farm storage of sticks after stacking by loader.
- chipped on farm direct into 38t HGV tipping trailer.
- driver and articulated truck arrive to collect the full trailer for delivery to power plant.
- A productivity of 7 odt/h was assumed, which equates to 0.35 ha/h.

(vii) Austoft harvester (cut and chip)

As for the Claas chipper system D above but using the Austoft modified sugar cane harvester at the assumed higher cost of £82.81 / hour (~ A$133/h). A productivity rate of 10 odt/h was assumed based on Forestry Commission trial results data.

(viii) Austoft harvester (cut and billet)

This is the same system with the same steps as for systems D and G above but with the Austoft harvester modified to produce billets rather than chips. The hourly cost is slightly lower as less power is required for billeting than chipping and less knife maintenance is required. This results in lower storage costs but the other input data remains the same (Fig. 4-12). The definition of a billet is a piece size which is bigger than a chip but is small enough to allow the bulk material to be handled by bucket loaders and on belt conveyors. It is large enough to allow air to naturally ventilate in a stack and prevent spontaneous heating. The work rate, machine costs and product bulk density were assumed to be the same for the Austoft harvester in both cut-and-chip and cut-and-billet modes of operation.

Figure 7-7 **Willow stick harvester with collection platform to accumulate load till drop off when full**

7.5.5 Large-scale system

This case study was based on a hypothetical commercial scale biomass-fired gasifier power plant with the fuel bought in from local growers under contract.

Combined cycle gas turbine plant

- **Capacity:**
  10MW$_e$ gross, 8MW$_e$ to be exported.
- **Fuel demand:**
  5 odt/h, @ 8,000 h/y (which assumes 91.3% availability) = 40,000 odt/y.
- **Fuel storage:**
  Need 34,000 odt stored on a hard stand area of >100,000 m2, the other 6,000 odt being fed into the plant directly on delivery during the harvest period of 50 days.

  a) Storage area filled over 90 days @ 50 odt/h, and being delivered for 8 h /day.
  b) Storage area emptied over 275 days @ 5odt/h for 24 h / day.

  Alternatively it could be possible to have long term storage off site and only short term storage and drying on site.

- **Drying:**
  A fuel moisture content of <20% (w.b.) is required for the gasifier:

  a) For chip piles at a drying capacity of 40kg/h/m2 using air at +28^{o}C above ambient from power plant waste heat (which can be assumed to be free), the floor area needed would be 125m^2 with a bed depth of 0.4m. A 300kW fan is required to give a constant fan pressure of 1.5 kPa. Energy consumption will be 80kWh/odt, which at £0.05/kWh is £4/odt (~A$0.08 c/kWh and ~A$6.4 /odt).

  b) Modified grain dryers could be used for drying the fuelwood where available on a farm, (the willow being harvested at a different season to the cereal crops). This will need:

     - a batch storage / drying system for 5 days fuel capacity = 720 odt chips.

  - a drying floor of 20 bays of 145m^2 each and 2m depth.
  - drying from 50% w.b. at harvest to 15% w.b. in 4 days using air at 23^{o}C.

The final desired form of woody biomass feedstock material is determined by the fuel specification of the conversion plant in terms of acceptable moisture content and particle size range. Delivery of fuelwood to the power plant site can be in a wide range of forms since the final feed preparation can be conducted on-site immediately prior to feeding the feedstock into the power plant. A wider range of fuel moisture contents may also be acceptable if the desired level can be reached by blending wet biomass with dry, or if the plant has some form of artificial drying facility. However a cost penalty to the grower for supplying wet fuelwood is likely.

Industry representatives' comments on the potential for this scale of operation[1] were as follows:

- Could use a single stem system on the large-scale area by felling larger trees later using forestry harvesters, transpirationally drying the biomass as whole trees, grapple feeding into chippers, and then replanting the area.
- Need to densify the crop to maximise payloads for transport. Based on growers' experience, a 90m^3 truck carries 22 wet tonnes of willow chips at a bulk density of 240kg/m^3 (150kg dry matter/m^3).
- Cheap chip storage using a pole barn and natural ventilation may be satisfactory to reduce deterioration and dry matter loss.
- Dry matter losses of only 8% over 6 months are reported.
- Using a well-designed grain drying floor and heated air, 200t of chips can be dried down from 38% m.c. to 8% m.c. in a 10 day period.
- If intention is to use grain drying facilities for SRC chips, then will need to have the grain out and sold before SRC harvest. Then can spread the capital costs of the dryer over more crops. If not sold at that time, will require construction of extra storage for the grain, which would be a cost against SRC production along with a share of the capital costs of the drier and the running costs.
- Billets are easy to store on farm if a good floor or ground surface is available and with no dust or spores. Less power is needed for artificial ventilation than for chips.
- When estimating unloading times, there is a need to include the inevitable queuing delay when delivering many loads to the power station.
- Large scale biomass purchasers can dictate the form of material delivered.
- Bales of SRC are compatible with bales of forest residues, straw (Fig. 4-9) and bagasse (Fig. 4-10) for handling at the plant, but some plants may also have a dump pit to unload the chips by tipping truck (Fig. 4-11).
- Harvesting the SRC as whole sticks with cheap headland storage and then chipping at the headland before transporting to the power plant has practical applications.
- On steeper terrain, in field chipping of SRC sticks may not be possible. Estimates are £1.65/odt to chip at the power plant but £8/odt to chip in the field. A sawmill chipper handling 80,000t / y costs £4/ wet tonne. Contract chipper charges are around £25/h.
- Further comminution of billets at the plant may require modifications to chipper designs.
- Bales are easy to measure by counting and the system would suit a range of crops and materials. Could take samples after chipping to confirm payment level on fuel quality but the cost of baling is a limitation.
- There is a risk of foreign bodies (e.g. stones) being in the fuelwood material supplied, especially if put on to the ground and later retrieved. Payment on quality must include a penalty for such contaminants.

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[1] Note all these quoted costs were based on 1998 data but remain relative to each other at current (2011) costs and prices.

- Farmers want ownership of the crop, and to be contracted by the developer who takes responsibility for harvesting the material (as for processing frozen peas). The power plant owner could hire contractors and oversee management of the crop, such that the farmers simply provide the land. The company could purchase a harvester for a contractor to use, lease it back and guarantee a minimum area.
- Projects are often proposed based on having to store fuel year round rather than use a mix of fuels coming on stream when needed. The model output, (system E,Fig32 Figure 7-11) clearly shows the advantages of direct delivery without storage if all year round harvest were possible.
- Reception areas for feed delivery at the plant have significant cost so there is a saving in having only one delivery system such as bales or chips, but not both.
- Whole bales could be burnt in heating systems. Billets could also be fed in.

Figure 7-8 Large square straw bales stored at the power plant ready for use

Figure 7-9 Bagasse baled and stored for use in a Queensland sugar processing co-generation plant during the non-cane crushing season

Figure 7-10 Chips being delivered to a Canadian wood-fired power plant by tipping truck

7.5.6 Small-scale system

This second option for the case study was based on an actual grid-connected, on-farm, co-generation plant in Europe, where the heat can be usefully used, the power exported and the fuel was grown by the farmer.

Gasifier and gas engine, operate 5,000 – 6,000 hours per year

- ***Capacity:***
  100kW$_e$, 80% of power exported; heat used for grain drying, space heating of house and buildings, and hot water.
- ***Fuel demand:***
  300 odt/y
  30 ha planted in SRC willow; 2 year rotation; yield of 10 odt/ha/y.
- ***Fuel storage:***
  Use bulk grain store if empty (i.e. if cereals have been sold off the farm by the time of harvest). If grain store not available, piles of chips outside are an alternative, ideally covered with plastic sheets.
- ***Drying - two stage:***
  Using heat from grain drying plant in batch drying at harvest, and using exhaust heat from co-generation plant immediately prior to delivery to the gasifier.

Comments from industry representatives on this small scale operation are given below:

- A front-mounted chip harvester/ tractor/ towed trailer would be satisfactory for on-farm use.
- An adapted maize harvester is possible - but it would be expensive at £60,000 so needs to be used for areas more than 400ha /y to achieve good cost recovery.
- At the farm scale, existing farm machinery should be used wherever possible to spread overhead costs.
- Use grain drying facilities where available for chips, or ventilate in a cheap store.
- Single stem harvesting could be an alternative option to coppicing. Yields of 8 odt/ha/y are feasible after 8 - 10 years growth under UK conditions. This system could be more suitable for poplar and eucalypts.
- Harvesting single stems with a simple saw blade on a tractor mounted frame has potential, dropping the trees and collecting them later.
- Sticks are good for natural drying but this is partly offset by handling difficulties.

A summary of the analysis is given in Figure 7-11 (£1 = A$ 1.6 approx.). As already noted, this data is from an overseas study conducted some years ago. Nevertheless, it still demonstrates the variability in costs for delivered biomass and highlights the need to optimise the biomass harvest and delivery system for a commercial bioenergy plant.

Systems E and B showed the lowest delivered fuel cost. This is not surprising as for these options there was no intermediate storage, the fuelwood being delivered directly to the plant for immediate use. This is appropriate in some circumstances, for example in Scandinavian district heating plants where the main heating demand season matches the winter season *Salix* coppice crops are normally harvested. In many other situations (such as for electricity generation or process heat), it is more likely that storage will be needed to provide a plant with fuel supplies all year round. This will increase the costs of supply due to the additional handling operations and the storage losses that may occur.

Where short cycle crops are to be the major fuel source, this study showed the potential cost reductions that could be achieved if the crop were to be harvested all-year-round[2]. Provisional

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[2] Sims R E H, Lowe H T, & Maiava T (1994). All year round harvesting of short cycle crops eucalyptus. Proc. 8th European Biomass Conference, Vienna. 1, 507-514.

studies, both in New Zealand on coppice *Eucalyptus* and in the UK on *Salix*, have shown that there is potential for such a management system without loss of yield over a sustained period. The resulting advantages, in terms of reduced dry matter losses together with lower handling and storage costs, justify further research for other crops such as oil mallee. Determining possible loss of future regrowth yield if harvesting at particular times (eg during summer drought or winter cold conditions) is needed.

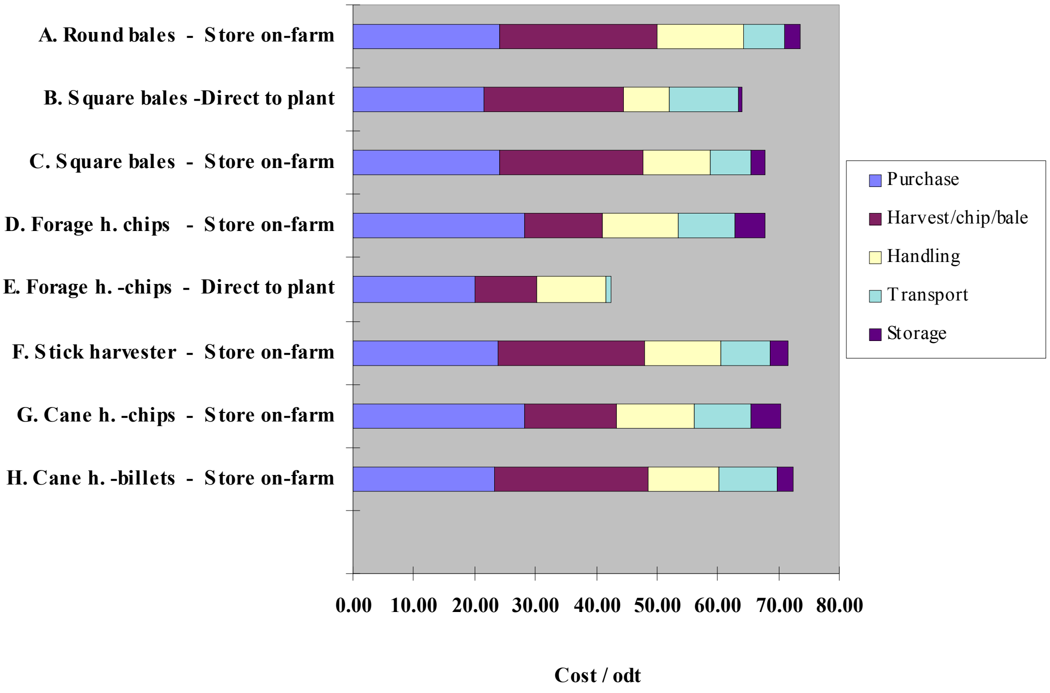

Figure 7-11 **A comparison of costs of a tonne of oven dry fuelwood delivered to the power plant gate (£/odt) for the eight selected system options**

The following general points and comments were raised by growers and industry representatives reviewing the project:

- The less travel on the field by the machines the better, to avoid soil compaction.
- Growers should seek value-added opportunities incorporating costs within their existing business.
- Contractors would be an alternative option to owning harvesting machinery, but are not yet operating in most regions due to limited demand.
- A simple single disc saw on a tractor-mounted frame could be more suitable for harvesting single stems than the use of manual chainsaws.
- Leaving bales in the field for later collection should be avoided as it could damage the coppice stools.
- Sticks and bales can be stored on headlands, but it would be economic to also plant the headlands to utilise all field space and to gain traction across the field when wet with machines

due to the root mat. Harvesting the headlands first is logical to give access, but then a place to store the material will still be needed.

If storage of fuelwood is necessary to provide an all-year-round biomass supply to a bioenergy plant, the costs will be increased significantly. This confirms the potential benefits of having a mix of fuels from a range of sources so that the amount of fuel going straight from source to plant can be maximised[3]. For a wood-fired plant such sources might include wood process residues, forest arisings and SRC. In some circumstances it may be appropriate to mix fossil fuels with the biomass to ensure a low cost supply. An example of such a flexible fuel plant is the 34 MWe co-generation plant operated at the Kinleith pulp and paper plant in New Zealand, which uses natural gas, bark and forest arisings as fuels. This reduces the risk associated with obtaining secure supplies of fuelwood for the long term and gives time for confidence to be generated in the supply chain by the plant operators.

In systems where fuel storage is required, the study showed that cut-and-bale or billeting systems could be competitive with chip systems and are worthy of further investigation. The big advantage of billets and bales, which was not fully evaluated in the analysis, is that the fuel delivered to the plant in these forms has a lower moisture content than chips from the same source and hence suffer less degradation when in store over any given period. However chipping and screening would probably be necessary at the plant to produce a consistent quality fuel, which would add to the fuel's cost.

The results of these studies clearly identified that the cost of biomass delivered to a conversion plant ($/GJ of useful energy output) is very much project specific. The delivered costs will vary with:

- Source and type of biomass
- Biomass production costs
- Harvesting costs, and seasonality
- Transport distance
- Moisture content
- Fuel quality (with a penalty for contamination)
- Capital costs of handling equipment relating to scale of plant
- Labour requirements.

In addition the capital cost of the plant and equipment, annual hours of use, discount rate, conversion efficiency, and load characteristics all affect the final heat or electricity costs. In all cases a detailed analysis is considered necessary to identify the cheapest production, processing and transport option from the many variations possible.

7.6 Study recommendations

The following recommendations are based on using state-of-the-art-technology, and assumptions that a fuel-wood supply is required all year round for power generation but that harvesting SRC willow is only feasible in winter (in the northern hemisphere). Detailed comments on each of these three options by industry representatives are also given.

7.6.1 Recommendation 1

Bale the cut SRC sticks or chunks into large round or square bales using existing agricultural baling machines mounted on a tractor/mower to give a one-pass machine with either:

- *bales dropped on ground for subsequent collection by tractor/front loader and transport to trailer or truck, or*

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[3] Sims R E H and Culshaw D (1998) Fuel mix supply reliability for biomass-fired heat and power plants. Proc. 10th European conference "Biomass for Energy and Industry", Wurzburg. June. pp 188-191. CARMEN.

- *bales carried to headland on baler for later collection by truck.*

It is possible that large-scale wood-fired power stations will use a mix of existing forest arisings and wood process residues as their main fuels, together with fuelwood from SRC. Therefore delivering the range of biomass material in a standard form is essential for cheaper and easier handling at the plant. If one truckload delivers biomass in the form of bales and the next truckload arrives as chips, it would be more difficult to handle and process than if all trucks delivered bales or all delivered chips. It must be borne in mind that for very large plants there may be one truck arriving every 5 – 10 minutes, so there is little time to handle the material. Hence having a standard form of delivery is essential.

Bales could be an ideal method of densifying the material to provide transport economies in terms of maximising truck payloads. However the costs of baling are likely to remain uneconomic unless higher throughputs can be achieved than at present and the balers can be used for other crops or purposes during the year in order to spread the fixed costs of ownership.

Since it would be extremely difficult to design a machine to pick up harvested sticks dropped on to the ground after cutting without damaging the remaining cut stems, a mower/baler machine combination seems a desirable design goal. The German company Deutz-Fahr has designed and tested just such a self-propelled prototype machine based on using either a Claas round baler or Heeston square baler. The concept was tested on willow biomass material in the field and by feeding in cut material in a test laboratory. The machine has not yet been made commercially available. An evaluation and cost analysis of this option is given in Systems A, B and C of the cost analysis.

Baling of SRC would also be suitable for the small grower supplying the power plant if a contractor in the locality could be hired or if the baler could be supplied by the owners of the plant for hire by the growers (which would help to maximise the use of the equipment and thus allow more time over which the fixed costs could be recovered).

This bale system could possibly be used by a small farmer growing SRC to supply any heat demand on farm or nearby if the bales could possibly be fed into a whole bale burner as developed for straw bales in Denmark (Fig. 4-13). However if a small gasifier is preferred, a small uniform piece size is desirable so the bale would first need comminuting. This would then require specialised and costly equipment.

Figure 7-12 Whole bale burner under development in Denmark

7.6.2 Recommendation 2

Develop a billet system around the Austoft sugar cane harvester or a chain cutter/stick harvester with a billeter mounted on the chassis. Either would need a conveyor with support trailer running alongside, or a mounted bin to carry billets to the end of the row for unloading hydraulically.

The advantages of this system were assumed to be as follows:

- Uses existing equipment, the base machine being available for chipping as well as for billeting but with some modifications required.
- Harvesting cost is cheaper than using whole stick harvesters.
- Work rate of around 0.25ha/h will require 16 x 10 hour harvest days to complete 15 ha of 10 odt/ha crops, so the harvester could be shared with 4-5 other growers on a syndicate basis if 50 harvesting days are available during the season.
- Acceptable soil compaction, even on wet sites, due to half-tracks.
- At a work rate of 0.4 ha/h and assuming 50 x 20 hour working days, the large scale plant would need 3 similar harvesters to harvest 1,000 ha / year.

Harvesting costs for billets delivered to the power plant would probably be similar to chips, but storage of billets rather than chips over long periods provides an overall advantage as a result of less dry matter losses whilst in store, lower energy inputs, and cheaper drying. (Note: use of the Austoft sugar cane billet machine was modelled using the transport programme and is reported as System H).

As mentioned earlier, year round harvesting, if agronomically feasible under UK conditions, would have a significant effect on harvesting costs and storage systems.

7.6.3 Recommendation 3

For small-scale systems on farms with existing grain drying facilities, a manual chainsaw or simple tractor mounted single disc saw blade used for older single stem trees and the trees later manually fed into a mobile chipper.

After cutting with a chainsaw or tractor mounted saw-blade, a simple harvesting system could be envisaged at this scale with a front-mounted chipper on a farm tractor with trailer towed behind. The chipper would be manually fed, which would limit the size of tree that could be harvested. However after being left to dry for some weeks, the tree weight would be less due to moisture loss. Trailer transfer when full would occur at the headlands. The commercial availability of such systems and the potential market for them need to be identified but they would use mainly existing equipment. The proposed drying system would also need to be fully tested and analysed to ensure it works with this chipped biomass material.

This concept has been well researched and developed, but now needs to be commercially proven.

It must be reiterated that the example above was developed in the UK, and it has been provided in the absence of similar studies carried out for Australian fuels or conditions. Nevertheless it serves to show the considerable differences between different delivery strategies, both for small and large-scale operations and even within similar requirements for fuel quantities. It is quite conceivable that different strategies would also be used across Australia according to differences in fuels available, existing machinery, harvesting limitations due to seasonal conditions or soil types, storage options and so on. Note also that the prices paid for renewable energy in the UK are greater than those paid in Australia, and so the economic viability of a process in the UK (or Scandinavia) does not immediately indicate that a similar system would be competitive in Australia.

8. Wood pellets

8.1 Summary

Finely ground and dried wood particles may be processed with readily available commercial equipment to make wood pellets. Compared with the original wood, these pellets have relatively high energy content and are easy to transport, store and utilise for heat and power.

The use of such pellets in Australia is generally limited to domestic heaters in certain regions. In Europe, however, pellet consumption is already significant for both domestic and industrial applications. Japanese consumers use pellets for heating, and at least one Japanese power company is trialling large scale pellet use for renewable electricity via co-firing. Most pellet production uses wood as the source of biomass. However, other forms of biomass such as straw may also be processed to manufacture pellets.

Pellet plants can be built at a wide range of sizes. Smaller plants will require less feed. Larger plants will generally offer economy of scale, but may also face greater costs for feed brought in from more remote growing areas.

8.2 Introduction

Wood pellets (see below) are short cylindrical pieces of biomass with a diameter 6 - 8 mm. They are produced from materials such as sawdust, cutter shavings, chips or bark by grinding the raw material to a fine powder that is pressed through a perforated matrix or die. The friction of the process provides enough heat to soften the lignin in the biomass. During the subsequent cooling, the lignin stiffens and binds the material together. The manufacturing process increases the bulk density of the feedstock from typically 100 to 650 kg/m^3. The energy content of pellets is approximately 17.5 GJ/tonne with moisture content of 8-10 percent.

Figure 8-1 Wood pellets

For some time pellets made from wood (and other biomass) have filled a minor niche in North American and European energy markets, mainly in the domestic heating sector. However in recent times wood pellets (also known as densified biomass fuel or DBF) have become an increasingly important energy source for both the domestic and industrial energy sectors, mainly as a result of increased emphasis on renewable energy sources.

Wood pellets have become much more widely used than many other forms of biomass for several reasons:

- High energy content
- Low ash content
- Ease of handling, storage and transport.

Bulk density - Solid biomass fuels are generally characterised by a lower bulk density (kg per cubic metre) and lower energy density (GJ per tonne), compared to coal. Solid biomass fuels often have relatively high moisture content, requiring specific designs for their combustion. One of the ways of making biomass a more attractive fuel is to simultaneously address these two relative disadvantages by densifying the biomass (at a cost) and by lowering the operational moisture content through, for instance, pelletising or briquetting the biomass.

Table 8-1 illustrates the bulk densities of some typical forms of wood biomass on a dry, ash free basis, to illustrate the much higher density of pellets compared with wood chips, sawdust and planer shavings.

Table 8-1 Typical wood biomass types and their densities

Wood Type	Bulk Density (kg/m3 daf)
Hardwood chips	227
Softwood chips	179-192
Pellets	556-625
Sawdust	161
Planer Shavings	97

As can be seen from Table 8-1, the bulk density of wood pellets is considerably higher than other forms of biomass from the same source.

Moisture content - In practice the moisture content of fresh wood chips, a common form of wood fuel, is generally in the range of 45-55 percent, giving an operational calorific value of the fuel in the range of 7 - 9 GJ/tonne. Wood pellets have moisture content in the range of 8-10 percent, giving a typical heating value of 17-18 GJ/tonne. Their uniform size, high density and low moisture content make wood pellets a versatile and reliable fuel. Wood pellets are easily conveyed by pneumatic means into bulk storage at domestic or industrial users. Alternatively, pellets can be purchased at the retail level from supermarkets in Europe and North America.

Figure 8-2 shows a typical bulk wood pellet tanker being loaded at the pellet factory.

8.3 Pellet markets

The two main established markets for wood pellets are the domestic heating market and the use of wood pellets as an industrial fuel.

8.3.1 Domestic heating market

This market mainly relates to wood pellet heaters for space heating and to small-scale boilers for water heating. Figure 8-3 shows a typical wood pellet stove in which the wood pellets are burned in a crucible, charged automatically via an auger. These stoves are extremely efficient (typically 96 percent) compared to open log fires. In the northern hemisphere, a prime application of wood pellet heaters is to replace oil burning and gas heaters.

Figure 8-2 Bulk wood pellet tanker in Sweden

Figure 8-3 Typical wood pellet stove

At a larger scale, wood pellets are now commonly used in several countries for district heating. Figure 8-4 shows a medium sized district heating plant in central Sweden that is fuelled by wood pellets. Shown are two pellet silos and the adjacent boiler housing.

Figure 8-4 Wood pellet fuelled central heating plant in Sweden

8.3.2 Industrial fuel market

A recent trend in some parts of the world is to use multifuel combustion plants, including use of biomass fuels. A prime example is the Avedore 2 Combined Heat and Power (CHP) plant located a few kilometres outside Copenhagen in Denmark. The output of this large CHP plant is 570 MW_e and 570 MW_{th} or, if operated in electricity only mode, 590 MW_e. This is the same scale as Australia's largest coal fired power station units. The plant has a multifuel capability, using both solid biofuels and natural gas. The main biomass fuel is wood pellets, which can provide up to 70 percent of the total input energy of the main boiler. Pellets are produced at nearby Køge in a large mill consisting of 18 pellet presses, and transported to the power plant by barge. On a yearly basis Avedore 2 typically consumes 150,000 tonnes of straw and 300,000 tonnes of wood pellets.

Figure 8-5 shows the Avedore 2 unit to the rear of the number 1 unit, which is coal fired.

Another example of large scale industrial use of wood pellets is at the Les Awirs Power Station in Belgium, where a 125 MW coal fired power station unit has been converted to be fuelled exclusively on imported wood pellets. In modifying the plant, its capacity has been derated to 80 MW_e to cater for the altered fuel. The pellets used here originate from all parts of the world. Pellets are delivered in a 'just in time' mode of operation by flat boats from the port of Antwerp, and also by road. The plant consumes some 350,000 tonnes of wood pellets annually, or approximately 1,000 tonnes per day. These pellets are milled on site to wood dust which fires the power plant. The utility has a stringent wood pellet certification scheme to certify the origin of the biomass, to ensure it is from ecologically sustainable sources. Another Belgian plant, the Rodenhuize Power Station similarly mills and uses wood pellets to produce 80 MW electricity.

Figure 8-5 Avedore 2 combined heat and power plant

8.3.3 World production and consumption capacities

IEA Bioenergy Task 40 has recently published a report on global pellet production, consumption and trade[1]. It notes that worldwide production capacity of pellet plants is increasing rapidly. Between 2009 and 2010 the global installed production capacity of the pellet industry recorded a 22% increase, reaching over 28 million tons. Anecdotal data for 2011 indicates that the production capacity may have reached 30 million tons. Figure 8-6 below shows production capacity by country for 2009 and 2010.

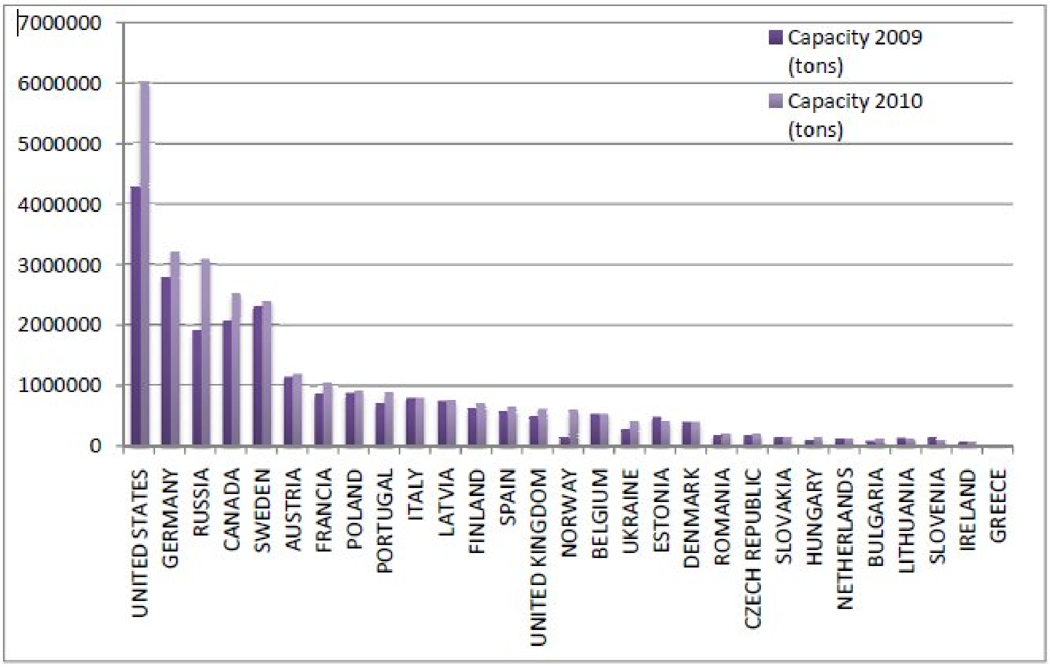

Figure 8-6 Wood pellet production capacity by country

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[1] Global Wood Pellet Industry Market and Trade Study IEA Bioenergy Task 40, December 2011

There is a low utilisation rate of installed capacity in many Northern Hemisphere pellet mills, only 53% on average. This is largely attributed to difficulties in sourcing feedstock at competitive prices. Figure 8-7 shows how pellet plant utilisation varies across Europe.

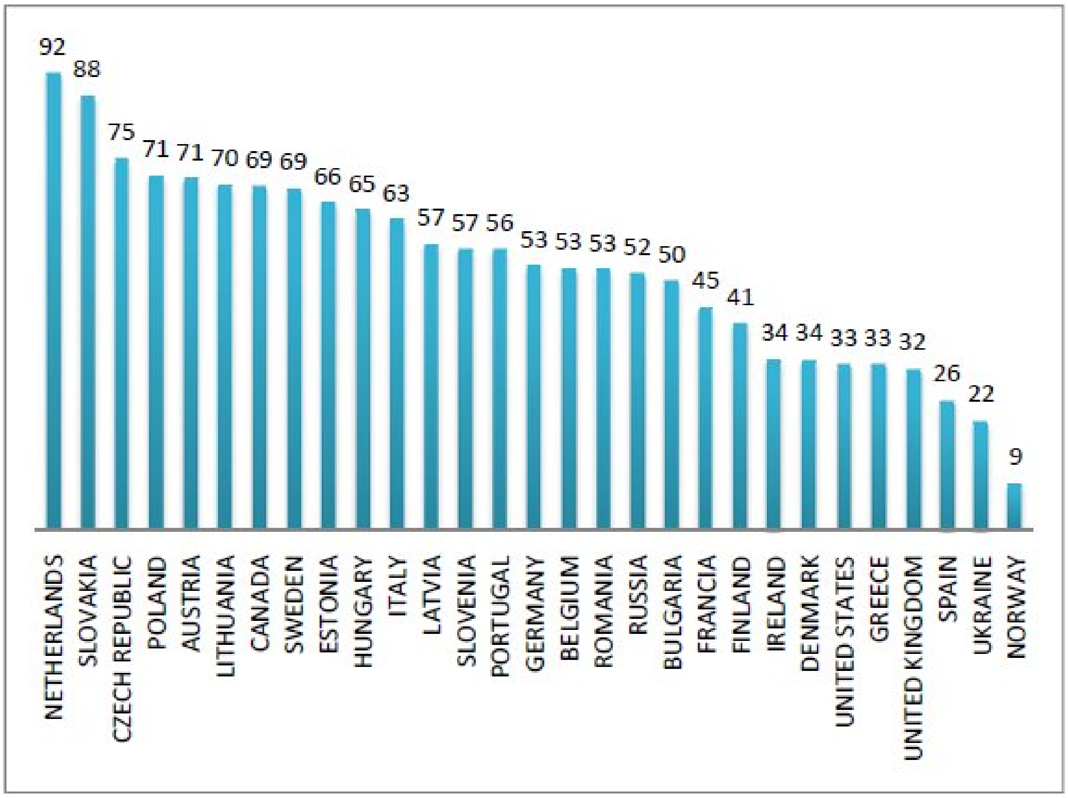

Figure 8-7 Wood pellet plant capacity utilisation rate (%) by country in 2010

The European Union is the main market for wood pellets and will remain so for the next few years. Between 2008 and 2010 EU wood pellet consumption increased by 43.5%, to reach over 11.4 million tons in 2010. This is nearly 85% of global wood pellet demand. In the same period, production of wood pellets in the EU increased by 20.5%, reaching 9.2 million tons in 2010 (equal to 61% of global production). The gap between production and consumption in the EU has grown from 262,250 tons in 2008 to 2,148,000 tons in 2010.

Significant trade between countries takes place. A number of European countries including Denmark, Italy, The Netherlands, Belgium and the UK consume considerably more pellets than they produce. Canada, the USA and several Eastern European countries produce more pellets than they consume and these countries provide the bulk of the trade across Europe and from North America to Europe.

8.3.4 Australia

Australia has both small scale and large scale pellet production facilities[2]:

- Plantation Energy Australia built a 250,000 tonne per year pellet plant near Albany in Western Australia. This plant exported pellets to overseas markets, primarily power companies in Europe, but ceased operations in early 2012, citing lack of suitably priced feed material and the strong Australian dollar as reasons[3].

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[2] Energy Pellet Developments in Australia. Liz Hamilton, Department of Primary Industries, Victoria. 2011

[3] http://www.abc.net.au/rural/news/content/201202/s3422461.htm

- Pellet Heaters Australia (PHA) commenced operations in Woodburn, NSW in 2003 and manufacture pellets from softwoods for the domestic heating market and also as animal bedding and spill adsorbents. Their original plant is based around a 3,000 tonne per year pellet machine.
- East Coast Wood Shavings in Gatton, Qld make pellets, mainly for animal bedding and litter markets. They use a similar pellet machine to PHA.
- Scottsdale Hop Growers in Scottsdale, Tasmania can produce up to 3,000 tonnes per year of pellets for animal bedding and domestic heating markets.

8.4 Pellet specifications

At present there is no single worldwide standard for wood pellets. However some pellet using countries have established standards and indeed some large industrial users (e.g. Electrabel in Belgium) and organisations (such as the US Pellet Heating Institute) have also established purchasing specifications.

EN 14961-2 is a recently developed European standard for wood pellets, which divides pellets into three broad categories, with different qualities and applications[4]. The characteristics of pellets that comply with this standard are summarised in Table 8-2[1].

8.5 Wood pellet production technology

A wide variety of biomass can be pelletised at various scales of production. Wood pelletising technology is available for throughputs of as low as 200 kg per hour to large-scale plants of up to 40 tonnes per hour (i.e. from less than 2,000 to more than 300,000 tonnes per year).

Wood pellets may be made from waste sawdust and other timber residues. A number of processing steps are required, some depending on the nature and quality of the feedstock which can be dry wood shavings, wet sawdust, wood chips or even whole tree trunks. The feedstock entering the pellet mill needs to be of a granular size of approximately 4 mm and a residual moisture content of approximately 10 percent. Accordingly, tree limbs require the maximum processing steps to debark, chipping of the fresh (moist) wood, drying of the biomass, dry grinding, pre-conditioning, pelletising, cooling, storing and loading for transport.

Drying can often be the most expensive step in the process. For wet raw materials, drying is reported as accounting for some 29 percent of the cost of the pellets[5]. A variety of industrial dryers exist and have been incorporated into wood pellet plants. Two main types of dryers are belt and drum dryers.

Dryers can operate with a range of heat sources: gas, oil or wood can provide the energy source for drying, which is facilitated by hot air, hot water or steam.

The dried feedstock is ground to a fine meal, generally using a hammer mill. The ground, dry biomass then enters the pellet mill, where pre-conditioning often occurs to soften the lignin in the wood (with steam). This reduces wear of the pelletising die and reduces production energy. There are numerous pellet mill manufacturers in both Europe and North America. Figure 8-10 is a showroom example of a typical pellet mill and replaceable dies, while Figure 8-11 shows an operating pellet mill at the Balcas pellet factory in Northern Ireland. The horizontal cylinder atop the mill is the preconditioning unit of the mill.

Figure 8-12 is a close up photo of a die at the Balcas facility. It consists of over 2,000 holes through which the wood is extruded into pellets. The newly formed pellets must be cooled following the pressing step, to ensure their structural integrity. After cooling the pellets can be stored in silos prior to transportation.

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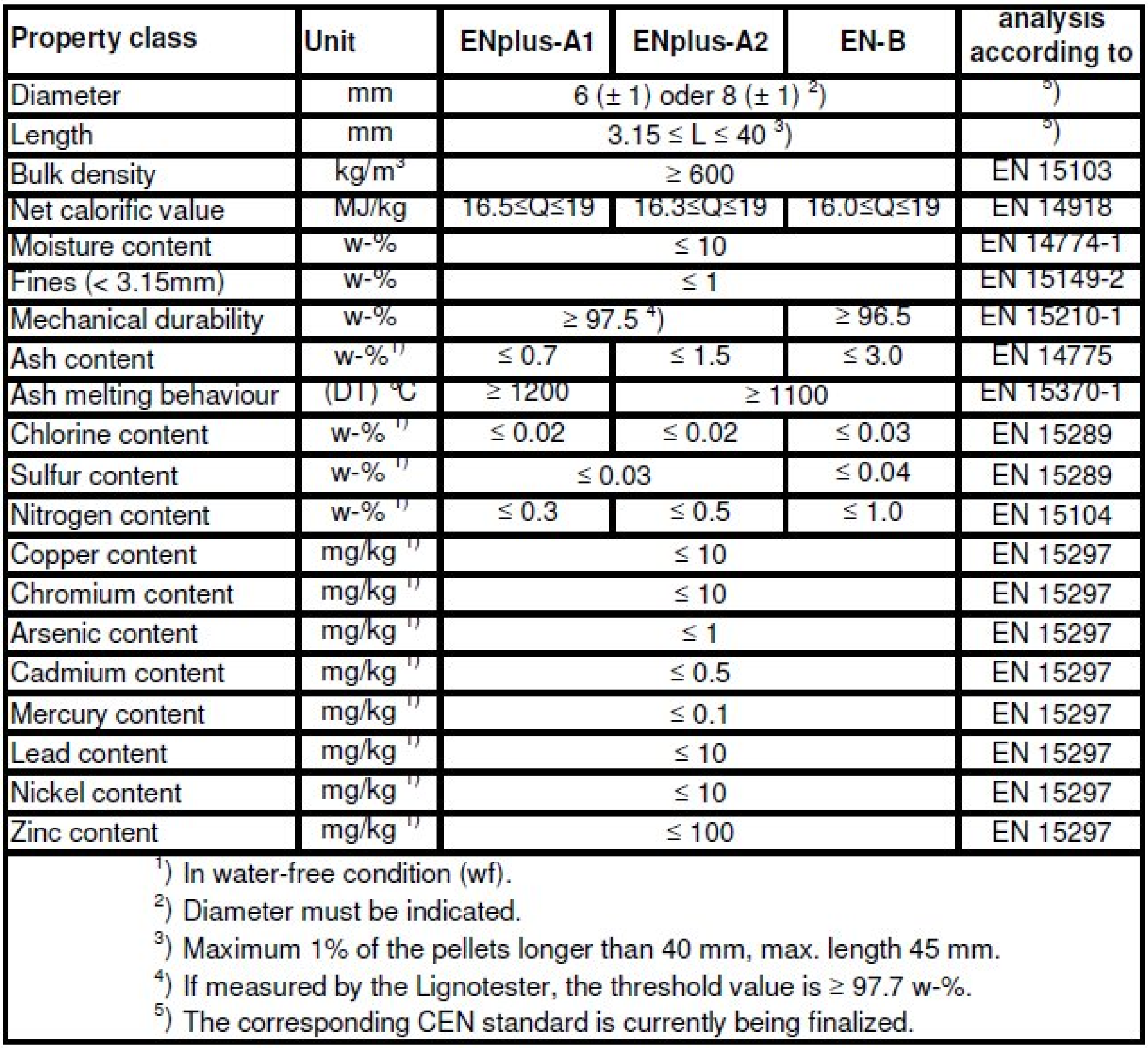
[4] http://www.pelletcouncil.eu/cms/wp-content/uploads/uitls 2011/02/ENplus-handbook-3.5.11.pdf

[5] Eubionet II and Expertos Forestales Agrupados (from a presentation delivered by Juan Prados in Melbourne on 27 February 2007)

Table 8-2 EN 14961-2 Wood pellets specification



Property class	Unit	ENplus-A1	ENplus-A2	EN-B	analysis according to
Diameter	mm	6 (± 1) oder 8 (± 1) [2]			[5]
Length	mm	3.15 ≤ L ≤ 40 [3]			[5]
Bulk density	kg/m³	≥ 600			EN 15103
Net calorific value	MJ/kg	16.5≤Q≤19	16.3≤Q≤19	16.0≤Q≤19	EN 14918
Moisture content	w-%	≤ 10			EN 14774-1
Fines (< 3.15mm)	w-%	≤ 1			EN 15149-2
Mechanical durability	w-%	≥ 97.5 [4]		≥ 96.5	EN 15210-1
Ash content	w-% [1]	≤ 0.7	≤ 1.5	≤ 3.0	EN 14775
Ash melting behaviour	(DT) °C	≥ 1200	≥ 1100		EN 15370-1
Chlorine content	w-% [1]	≤ 0.02	≤ 0.02	≤ 0.03	EN 15289
Sulfur content	w-% [1]	≤ 0.03		≤ 0.04	EN 15289
Nitrogen content	w-% [1]	≤ 0.3	≤ 0.5	≤ 1.0	EN 15104
Copper content	mg/kg [1]	≤ 10			EN 15297
Chromium content	mg/kg [1]	≤ 10			EN 15297
Arsenic content	mg/kg [1]	≤ 1			EN 15297
Cadmium content	mg/kg [1]	≤ 0.5			EN 15297
Mercury content	mg/kg [1]	≤ 0.1			EN 15297
Lead content	mg/kg [1]	≤ 10			EN 15297
Nickel content	mg/kg [1]	≤ 10			EN 15297
Zinc content	mg/kg [1]	≤ 100			EN 15297

[1] In water-free condition (wf).
[2] Diameter must be indicated.
[3] Maximum 1% of the pellets longer than 40 mm, max. length 45 mm.
[4] If measured by the Lignotester, the threshold value is ≥ 97.7 w-%.
[5] The corresponding CEN standard is currently being finalized.

An example of a belt dryer is shown in Figure 8-8 at the Balcas pellet plant in Northern Ireland.

Figure 8-8 Belt dryer

Figure 8-9 **Drum dryer**

Figure 8-10 **Pellet mill and dies**

A question that often arises is the amount of energy required to manufacture and transport the wood pellets, as a proportion of the embodied energy in the wood pellets themselves. With pellets manufactured from dry wood splints or wood dust, the energy input for the pellet production is approximately 3% of their energy content. With damp and uncut wood the energy input for the production can rise to between 5 and 20 percent of the energy content[6].

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[6] Krapf 1999 as quoted in Ecolabel report

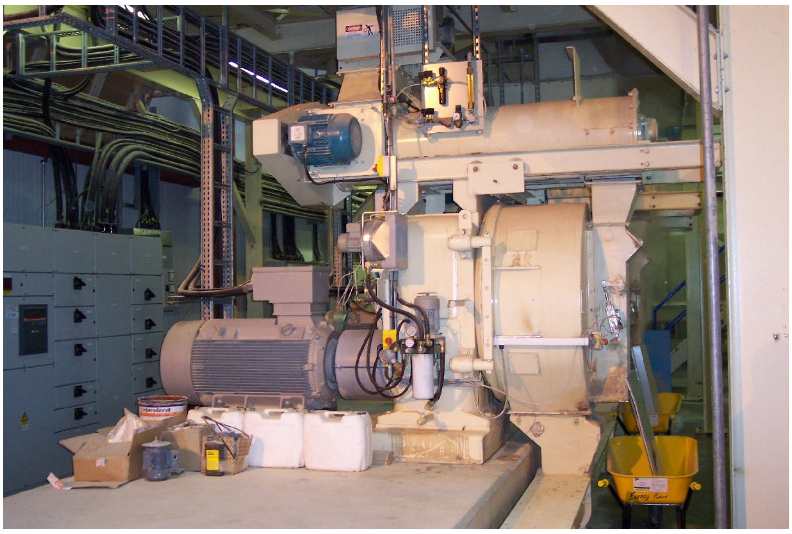

Figure 8-11 Pellet mill at Balcas pellet factory, Northern Ireland

Figure 8-12 Pellet die

8.6 Biomass requirements

Wood pellet properties are largely determined by the properties of the feedstock. Wood pellet specifications typically require low ash and other impurities, low moisture content, and a high calorific value. The domestic heating markets in Europe are currently supplied mainly by pellets made from softwood, which can be expected have different density and colour from Australian hardwoods such as mallees or other plantation eucalypts.

Stemwood will have a lower level of ash and contaminants than other parts of the eucalypt tree. Tests would need to be conducted to examine the effect of leaf and twig matter in the pellets. The biomass would need to be carefully processed from harvest to pelletising, to ensure extraneous dirt does not add to the level of ash in the feedstock.

8.7 Storage and transportation

The most widely used storage systems for wood pellets are silos. An example of wood pellet storage silos is shown in Figure 8-4. It is unusual to store pellets at production plants for any length of time, with on site storage typically being less than 10 percent of the annual production capacity. Some smaller pellet producers also use warehouses.

Some domestic markets for wood pellets in overseas countries are serviced by wood pellet tankers, from which the pellets are blown into storage hoppers, or through a variety of sizes of bags of pellets. The bags may be purchased individually, or can be supplied on a pallet of some 50 bags. Figure 8-13 below shows pallets of wood pellets.

Figure 8-13 Bags and pallets of wood pellets

Wood pellets are currently transported in bulk via railway cars, articulated tanker trucks, by barges and ships. Some precautions are necessary to ensure health and safety considerations are met. Hazards to be avoided are breathing in wood dust, build up of micro-organisms, fire and dust explosions. Well documented handling procedures and precautions can mitigate these hazards.

8.8 Cost of production

A number of factors influence the capital and operating costs of a pelletising facility, and hence the per tonne production cost of the pellets. These factors include the location and scale of the plant, the specification placed on the product wood pellets, the nature and cost of the feedstock, the need for drying, local cost of electricity for running the motors and the cost of energy for drying the feedstock, cost of labour, cost of onsite storage. Following production, packaging, and transportation costs will impact on the competitive position of the pellets in any given market.

The and Rosenberger[7] published a comprehensive analysis on the cost of producing wood pellets in Austria. They examined nine pellet plants in Austria. Analysis included costs of all plant, equipment, offices, market planning as well as utilisation factors and maintenance costs. It also included the costs of bio-additives, steam used in the conditioning units, storage costs, and shift labour costs.

This study determined ex factory production costs (in 2002) of between €78.6 and €101.2 per tonne for wet raw material and between €52.2 and €81.3 per tonne for dry raw material. Figure 8-14 shows the distribution of cost factors in Austria when using wet raw biomass, while Figure 8-15 shows the cost factors when using sufficiently dried raw material for pellet manufacture.

More recently Pirraglia et al[8] carried out an analysis of the costs of pellet production in North America, modelling a 75,000 tonne per year pellet plant. They estimated the cost of production at US $204 per tonne, with biomass purchase making up 27% of the total cost, energy 17% (largely for drying) and labour 24%.

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[7] 1st World Conference on Pellets, 2002

[8] Techno-economical analyses of wood pellets production for US manufacturers. By A. Pirrraglia, R. Gonzalez & D.Saloni. (2010) BioResources 5(4) 2374-2390. http://www.ncsu.edu/bioresources/BioRes_05/BioRes_05_4_2374_Pirraglia_GS_Techno_Econ_Anal_Wood_Pellets_US_Prodn_1108.pdf

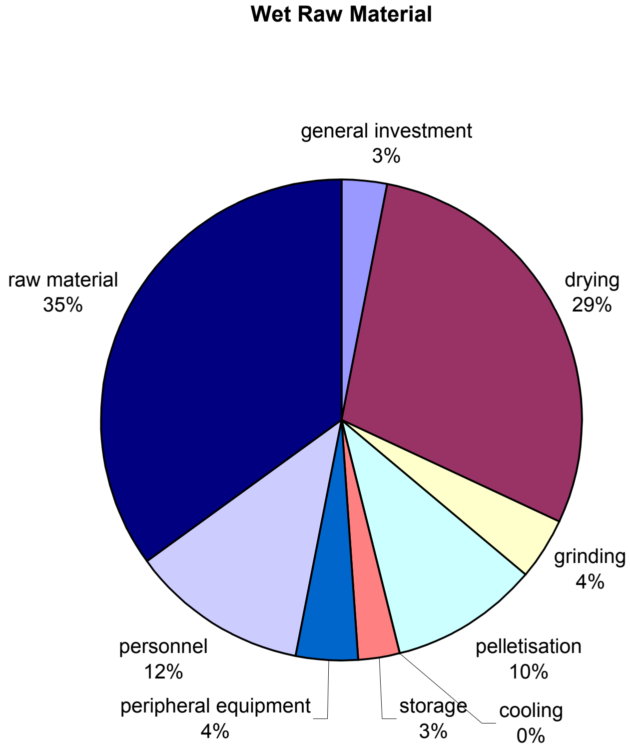

Figure 8-14 Cost distribution using wet raw material

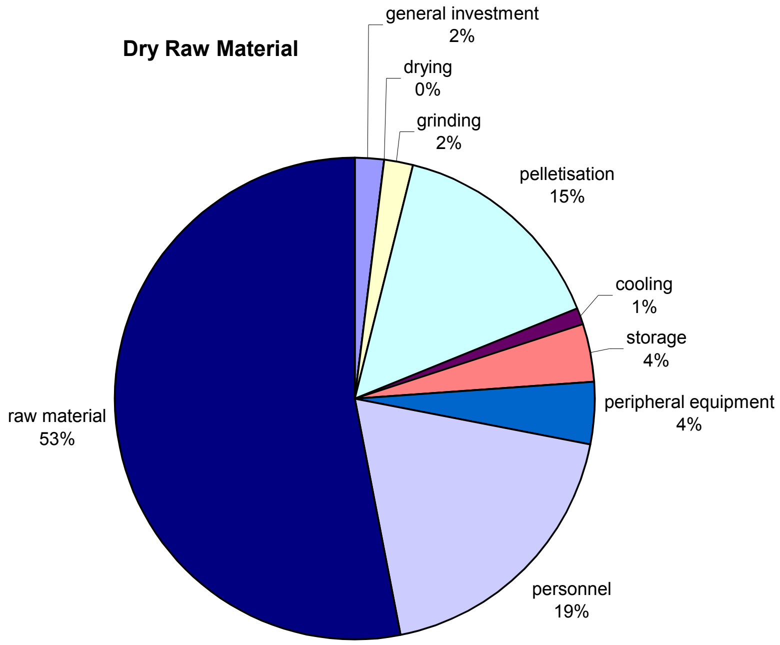

Figure 8-15 Cost distribution using dry raw material

9. Supply and delivery of mallees

9.1 Summary

This chapter presents a case study of mallee eucalypts developed for use as a coppicing woody crop with biomass harvests taken on a 4 year cycle. It presents detailed specification and economic modelling of the biomass production system and supply chain. The study is set in the context of the two decades of development of native mallee species as short-cycle woody crops in the south west of Western Australia. The planting layout consists of narrow belts of mallees, widely spaced within the existing agricultural systems that typically involve sequences of rain-fed crops and pastures.

The wide dispersal of belts on farms provides a large tree/agriculture interface, enabling belts to provide benefits to and capture surplus resources from the adjacent crop/pasture land. This chapter reports on the potential value of these associated benefits (called co-benefits) of integrated mallee/annual crop systems. Co-benefits include the reduction of water-logging and groundwater recharge; shelter and protection for crops, livestock and soils; protection for biodiversity assets and infrastructure. Belts of mallees dispersed in farmland also impose competition on the immediately adjacent agriculture and this competition zone is accounted for in the analysis. The competition impact is moderated by harvest but coppice growth and the retained root system can restore the full intensity of competition within 4 years.

This delivered cost of mallee biomass includes allowances for the opportunity cost of the land occupied by the tree belt; cost of competition zone; site preparation, planting and establishment of the tree crop; harvest and haulage; supply chain management and administration of contracts and operations; and road transport from farm gate to the processor. It is estimated that for a mature industry the delivered cost of biomass is likely to be in the range of $53 to $70 per green tonne (typically 45% moisture), assuming adoption of current technologies, establishment of efficient business services and economies of scale.

In addition to revenue generated from the sale of biomass, the values of co-benefits are estimated to be in the range of $2 to $15 dollars per green tonne. If growers are able to take advantage of the co-benefits and consider them as off-sets against the opportunity cost of land, then in a competitive market, the biomass price may be reduced to as low as $38 per green tonne. Furthermore, current research in genetics, nutrition, water use physiology and hydrology provides promise for additional strong reduction in the biomass price. These results were estimated for a region with annual average rainfall of 500-600 millimetres and are broadly transferable to all dryland agriculture regions of southern Australia with similar rainfall.

Significant gains can be made in scale, efficiency and profitability of industries based on farm grown woody biomass by further improvements in the design and productivity of mallee production systems; better understanding of their complementary role in dryland agriculture; advances in the technology of conversion of biomass to electricity and liquid fuels; and cost reduction in the farm-to-factory supply chain. Further impetus for the expansion and resilience of this emerging industry could be provided by policies that better recognise that industries based on broad scale revegetation with woody crops will improve agriculture’s ability to make a positive impact on the environment; increase national fuel supply security; improve natural resource management (e.g. dryland salinity); and enhance the conservation of biological diversity.

9.2 Introduction

Over the past two decades, mallee eucalypts have been extensively researched to better understand their potential for environmental and commercial benefits on and off farm in dryland agricultural regions. Section 9.3 below provides a summary of work already undertaken to develop mallee trees as a useful perennial crop in these dryland regions.

Mallees have already been planted by more than 1,000 farmers in Western Australia, however they are not yet established as an ongoing farming business that supplies biomass to commercial customers. Prospective biomass customers need to know the likely costs of such biomass. The proponents of a mallee industry need to know whether they can meet the expectations of customers as their industry matures. In addition to meeting the cost requirements of future customers, mallees must be sold at a price that adequately reimburses growers and the other participants in the mallee supply chain. The study reported in this chapter was commissioned to better understand the commercial supply chain and thus provide useful costing information to all these different groups.

Costs have been calculated for mallee biomass delivered to bioenergy customers. These costs have their basis in existing data on dryland farming and the pre-commercial mallee industry, extrapolated to a mature mallee supply industry, some years in the future. It is expected that economies of scale and efficiencies gained though further research and operational experience will ensure that the biomass supply costs for a well established industry will be significantly lower than they would be for the industry today.

The following sections describe the major issues considered in the study. More specifically:

Section 9.4 presents the study methodology and results.

Section 9.5 examines production and delivery costs for mallee biomass. It considers the costs to farmers due to land use and competition, and the effect of layout on these costs. It then considers the expected costs for harvesting and transport from the in-field harvester through to the customer.

Section 9.6 examines the revenues and benefits attributable to mallees. Direct revenues accrue through sale of biomass but the mallees can offer multiple additional benefits. These include carbon sequestration, water and salinity management, shelter and livestock protection, and benefits in biodiversity and protection of natural resources and infrastructure both on and off farm.

Conclusions and references are provided at the end of this chapter.

9.3 Background to mallee development

Development of mallee as a biomass crop for integration into the agricultural systems of the south-west of Western Australia (WA) began in the early 1990's in the then Department of Conservation and Land Management (CALM, now Department of Environment and Conservation, DEC) (Bartle & Shea 2002, URS 2009). This development was motivated by the potential of a profitable woody crop that would also help remedy the natural resources management (NRM) problems generated by agriculture reliant on annual crops and pastures.

This study draws on nearly two decades of experience with development of mallee as a biomass crop in Western Australia, where some 15,000 hectares of mallee have been planted, backed by continuing R&D input to all aspects of mallee agronomy, harvest, supply chain and processing. This includes design and implementation of measures to capture the co-benefits of integrating mallee crops into conventional wheatbelt agriculture (Sparks et al. 2006; Worley Parsons 2009). A large body of literature has accumulated, much of which is referred to in recent publications (Abadi & Cooper 2004; Abadi et al. 2006; Bartle & Abadi 2010; Peck et al. 2012). Early mallee development in WA also drew heavily on the long history of eucalyptus oil production from native and planted stands of blue mallee (*Eucalyptus polybractea*) in NSW (West Wyalong district) and Victoria (Bendigo region) (Davis 2002).

There are many mallee species that are prospective for use as woody crops but a range of species with high leaf oil content has been selected for initial development, including *E. polybractea, E. loxophleba subsp. lissophloia* and, for drier regions, *E. kochii subsp. plenissima*. The oil in the leaf of these eucalypts has a small traditional market but there is potential for large scale industrial use (Soh & Stackowiak 2002; Leita et al. 2010).

The leaf oil is a deterrent to grazing of the trees by livestock, making it feasible to grow mallees in dispersed, narrow belts without the need for fencing to protect them from livestock. After harvest (cutting at ground-level) mallee trees regenerate readily by coppicing (sprouting) from the retained rootstocks. The ability to sustain regular harvest over many decades has been demonstrated in native stands managed for production of eucalyptus oil (Davis 2002). Hence mallee coppice systems can potentially provide a sustainable long-term supply of renewable feedstock for energy, fuel and industrial products (Yu et al. 2009).

The terms short rotation woody crops (SRWC) and short rotation coppice (SRC) are widely used in the international literature (e.g. Dickmann 2005). In Australia, where there has been strong focus on close integration of the woody crop into the system of agriculture, the terms 'short cycle woody crops' or 'short cycle coppice' are preferred to avoid confusion with the concurrent use of the term 'rotation' in the agricultural context. Coppice is the regrowth of the plant after harvest (or after fire or drought), which occurs from active buds on the base of the stem.

Biomass yield of 10 to 20 green tonnes per hectare per year can be achieved when mallees are grown in widely spaced two-row belts in alley systems in regions with adequate rainfall and suitable soil types. Green mallee biomass typically contains 45% moisture (Peck et al 2012). Alley systems provide wide bays for conventional agriculture between narrow belts of tree crops. Growing mallees in belt and alley system optimises the tree/agriculture interface and it offers the trees the opportunity to capture additional resources, especially water from the alleys of agricultural land, as shown in Figure 9-1 below.

Policies that provide incentives for adoption of renewable energy and that limit emission of greenhouse gases will encourage the development of the mallee biomass industry if it can become a cost-competitive feedstock. There are many options for conversion of mallee biomass to bioenergy. Combustion to generate heat or electricity can use technologies that are already commercially available and new technologies for production of biofuels are emerging, as described elsewhere in this report and in Bridgwater (2011), Mohan et al. (2006) and Cherubini et al. (2009). Production and use of mallee biomass for biofuels offers greater greenhouse gas reductions than the use of first generation feedstocks. This was demonstrated by Wu et al. (2008) showing that the mallee biomass production system could produce advanced generation (woody or lignocellulosic) bioenergy feedstock at a higher energy ratio than first generation feedstocks (starch and plant-oils).

Figure 9-1 Mallee belts planted on a wheat belt farm in Western Australia

This study reported in this chapter investigated the cost of mallee biomass delivered to processors after allowance for a sufficient return to growers and other businesses along the supply chain (Bartle & Abadi 2010; Peck et al. 2012). The context for this study was assumed to be a mature and well integrated mallee biomass production system operating within the conventional dryland agriculture of the 500-600 mm rainfall zone in Western Australia.

All growing, harvest, haulage and delivery costs for chipped biomass were estimated. These include estimates of the variable and fixed costs as well as a profit margin for the business enterprises and the contract services that will be required to make the whole production chain operational. The costs used in this analysis are those considered to be achievable in the medium term after the high initial costs associated with new business establishment and scaling-up have been streamlined. Considerable scope for better design and technology to reduce costs and increase yields was demonstrated in a recent analysis for the Australian Government Second Generation Biofuels R&D Program (Mendham, in press). These results are not incorporated into this analysis but will be discussed in Section 3 to indicate potential future reductions in biomass cost. Although these estimates of the delivered cost of biomass are based on mallees grown in farming systems of the south west of WA they could, with minor modification and local data, be adapted to other regions in southern Australia.

9.4 Analytical method and results

The delivered cost of biomass is estimated by analysis of costs and revenues for each step of the supply chain for a notional bioenergy project that would utilise 150,000 tonnes of biomass per year (measured on a dry basis). Such a project would require an annual production of 245,000 green tonnes of biomass (which is typically at 45% moisture). A project life of 50 years is considered.

9.4.1 Marginal analysis of mature industry

The analysis carried out for this chapter assumes a mature mallee biomass production and processing industry. This means the adoption of currently understood production and supply chain technology, establishment of an efficient service industry and achievement of economies of scale. It is a marginal analysis that estimates a range for the long term equilibrium price of biomass. This is the price that is acceptable to the whole supply network for the marginal (or last) unit of biomass that is grown, harvested and delivered to an operational processing plant that regularly processes large volumes of biomass (Miranowski & Rosburg 2010). The costs per green tonne of biomass (expressed in 2012 Australian dollars) are the aggregate of marginal costs of all the capital, material and labour resources used by farmers and those firms that are likely to provide services along the supply chain. As such, it is not an exercise in full capital budgeting or discounted cashflow analysis. The value of major co-benefits of a mallee industry have also been estimated and are expressed in the same units.

The analysis assumes that the profitability of mallee must at least match or break-even with that of the existing agriculture. Data for the ‘net operating surplus’ of agriculture (all revenues less all costs expressed on a per hectare basis) is used to provide the measure of profitability of agriculture in the region studied, and the break-even target for the mallee operation (Planfarm-Bankwest 2012). The break-even price effectively describes the extent to which the revenues from mallee crops must exceed the costs of production. Using the results of marginal analysis in this way enables stakeholders to assess the potential value of long term participation in the mallee biomass industry.

9.4.2 Overview of results

A summary of the study results is provided below in tabular form. Table 9-1, Table 9-3 and Table 9-5 list all cost and revenue items, and Table 9-2 and Table 9-4 provide brief background information about each item.

For a mature mallee industry, the cost of green biomass delivered during the 50 year life of the project is likely to be in the range of $53 to $70 per green tonne, as shown in Table 9-1. This estimate accounts for the opportunity cost of the land occupied by the tree belts plus the competition imposed by trees on the adjacent agricultural crops; site preparation, planting and establishment of the tree crop; harvest and in-field transport (haulage); supply chain management and administration of operations and finally road transport from farm gate to the processor.

Table 9-1 Components of cost of mallee biomass delivered to processor

Components of delivered cost	Expected range in $/green tonne	
	Lower estimate	Upper estimate
Opportunity cost of land (belt and competition zone)	20	21
Planning, establishment and planting of trees	1	4
Fertiliser to replace nutrients exported in biomass	3	7
Harvest and haulage to road side	20	23
Road transport from farm gate to processor	5	9
Supply chain management and administration	4	6
Total delivered cost range (excluding co-benefits)	53	70

Compensating the landholder for the land occupied by the trees and the competition they impose on adjacent agricultural crops is about 35% of overall costs. The other major cost is harvest and on-farm haulage, also totalling about 35% of costs.

Table 9-2 Description of cost items listed in Table 9-1

Cost item	Brief explanation
Land opportunity cost consisting of: land area occupied by the belt Competition imposed on adjacent agriculture	Opportunity cost of land is the value of the 'net operating surplus' of land displaced from agricultural production. Valuation expressed on a per tonne basis also depends on biomass yield, which is a function of site characteristics, belt design and the value of co-benefits. The range used here reflects two options for the width of the tree belt. This is an important design parameter but gives a narrow cost range, which is further discussed in Section 3. Other substantial variation arising from seasons, soil types, costs, management input and commodity prices are averaged out in the net operating surplus. The competition imposed on adjacent agriculture is due to depletion of soil moisture and nutrients by the trees.
Establishment	Routine operations carried out by growers or contractors, ranging from cost of seed and nursery stock to preparation of the land, planting and associated costs. The difference between the lower and upper estimate of this item accounts for alternative modes of financing the upfront establishment cost.
Fertiliser	The initial assumption is that the cost of fertiliser should be that required to replace nutrients exported in mallee biomass. Although mallees will initially be able to utilise stored nutrients they will require applied nutrients to maintain long-term productivity. It is assumed that the nutrients are applied at the same time as application of fertilisers for agricultural crops or pastures in the alleys. This will reduce number of operations and minimise cost.
Harvest and in-field transport	Purpose-built harvester operates as a continuously travelling machine to simultaneously cut and chip trees and load the chips into on-farm transport, which takes the chipped biomass to a transfer point for loading into road trucks.
Road transport	The cost of biomass transport from the farm landing to the processing plant. The upper estimate is for transporting biomass within a 50 km radius, while the lower value is for within 10km radius of the processor.
Supply chain management	Costs associated with administration and contract management services, including recruitment of growers. The main costs are staff and office space required to operate the supply chain with minimal buffer stocks. The range indicates cost reduction with scale.

The price that buyers pay for woody biomass feedstocks must compensate the suppliers and operators along the supply chain for the costs of production and delivery of the biomass. Typically, buyers and sellers evaluate the feasibility of the prospective business, and enter into a pricing arrangement that they expect will make a viable business. The on-farm co-benefits such as reduction of water-logging in the alleys, conserving the natural resources of the farm, shelter for livestock, and carbon sequestration revenues can provide extra motivation for growers. This may, in turn, be reflected to some degree in their preparedness to accept a biomass price that is lower than their direct cost of production. Farmers and regional communities may also anticipate economic benefits from mallee and bioenergy industry development in the form of diversification of the farm business, options to manage farm green house gas emissions, and regional industry creation with increased local employment and other social benefits. There are also potential public benefits from improved management of biodiversity and other off-farm co-benefits (positive externalities) that may attract public funding contribution for planting of mallee belts. Some of these benefits have been assessed in this case study and estimates of their value expressed in $/green tonne of biomass are given in Table 9-3.

Table 9-3 Value of co-benefits of mallee biomass production systems.

Value of co-benefits	Expected range in $/green tonne delivered to processor	
	Lower estimate	Upper estimate
Reduced water-logging of crops in alleys in some seasons	1.00	10.10
Protection of biodiversity & public assets from salinity	0.82	2.80
Revenue from carbon sequestration (based on CFI)	0.00	2.17
Reduced livestock mortality - shelter and protection	0.06	0.41
Total value of co-benefits	1.88	15.48

The results given in Table 9-3 (further explained in Table 9-4) show that mitigation of water-logging in years with well above average rainfall is the most significant on-farm benefit, at between $1 and $10 per tonne of green biomass. Mallee plantings will also have benefits beyond the farm gate, which could justify public investment in biomass production. The reduction in rate of salinisation of public assets including biodiversity assets is valued at up to $2.80 per green tonne of biomass. On-farm benefits of shelter, erosion control and livestock protection were small in relation to cost of biomass. If harvested mallee plantings qualified as a form of carbon sequestration under the Carbon Farming Initiative (CFI), the revenues would be $2.20 per green tonne of biomass.

Table 9-5 summarises the range of costs, revenues and co-benefits for mallee biomass production in a region with a mature industry, expressed per green tonne of biomass delivered to a processor, where the co-benefits are deducted from the break-even or biomass selling price.

Biomass revenue is the selling price required to cover the full cost of production and delivery. It may be reduced by value of co-benefits, assuming that growers and the biomass production industry at-large will be able to take account of co-benefits. On farms where co-benefits of mallee plantings exist and if growers are able to take advantage of their full value and consider such positive impacts as off-sets against opportunity cost of land then the biomass price at the processor's gate may be reduced to as low as $38 per green tonne.

Table 9-4 Description of co-benefits of mallee biomass production systems listed in Table 9-3

Benefit item	Brief explanation
Mitigating water-logging and reducing recharge	Trees reduce surplus water in their vicinity, which if left unabated in susceptible soils and sites can reduce crop yield, increase groundwater recharge and contribute to salinity. This benefit only accrues in seasons with well above average rainfall.
Protection of biodiversity and other private and public assets	Belts of mallees increase biodiversity of native fauna. They also provide benefits for natural resource management at the local catchment scale. These values will vary between sites and require careful analysis before monetiation as the benefits could be widely distributed both on and off farms.
Carbon sequestration	Includes payments for sequestration of carbon in below ground biomass (roots) and long run average above ground standing biomass net of harvested material as indicated under the CFI.
Shelter and protection for livestock	Belts of trees can provide shelter for livestock and reduce lamb mortality during cold rainy periods, during extreme weather events, or in wind exposed situations.

Table 9-5 Summary of the range of costs, revenues and co-benefits for mallee biomass production

Components of cost, revenue and co-benefit	Expected range in $/green tonne	
	Lower estimate	Upper estimate
Delivered cost of biomass from Table 9-1	53.00	70.00
Total value of co-benefits	1.88	15.48
Range of biomass selling price required to break-even after deducting the value of co-benefits	37.52	68.12

Note: to derive the full range of biomass selling price, the upper estimate of the co-benefits is deducted from the lower estimate of selling price, and vice-versa for the upper estimate of selling price.

9.5 Production costs

Each of the main production costs is now considered in turn. These are:

- The opportunity cost of the land that is planted to, and affected by, the mallee trees
- Establishment and maintenance costs for the trees
- Costs for harvest and on-farm transport
- Road transport to the bioenergy plant
- Costs for supply chain management and administration.

9.5.1 Opportunity cost of land

Adoption of new crops has some uncertainty and risk (Just 1993; Abadi Ghadim & Pannell 1999; Pannell et al. 2006). Farmers can find it difficult to estimate the returns from energy crops due to uncertainty over costs, potential yields and prices (Sherrington et al. 2008). In comparison, farmers are well aware of returns from conventional crops and the prices and yields at which they would be profitable (Fisher et al. 2010). While many landholders are committed to the long term sustainability of their agricultural enterprise, their major challenge is short-term economic viability. When considering adoption of mallees as an energy crop their primary question is whether a mallee crop can generate a profit comparable to other land use options.

To calculate the opportunity cost of land occupied by the tree belt (in dollars per green tonne of mallee biomass) it is necessary to first identify the optimal belt and alley design and estimate the biomass yield under a harvest regime that optimises the long term yield from the trees. Next is consideration of the net operating surplus available from the same area of land under alternative uses. The net operating surplus is a measure of the value of the conventional agricultural production that would be displaced by mallee belts. Net operating surplus data are available in the Planfarm-Bankwest Benchmarks (2012). For the 500 to 600 millimetre rainfall zone in the south west of WA the net operating surplus per effective hectare of land is around $105 (in nominal terms) when averaged over the last two decades. Note that this surplus includes overheads and fixed costs such as rates, electricity and insurance but not financing costs, taxes or operators' (farmers) personal costs.

In southern Australia the conventional dryland agricultural activities are cereal grain crop rotations of varying lengths alternating with a break crop, such as canola or a pulse crop, or a pasture phase of two- years duration for grazing livestock. Grain crops are typically cereals such as wheat and barley, oil seeds such as canola and grain legumes or pulse crops such as peas and lupins. The most common livestock enterprise is sheep for production of wool and meat (Fisher et al. 2010, Bankwest Benchmarks 2011).

(i) Mallee belt design and site selection

Mallee belts must be skilfully designed and managed in order to achieve an optimum mix of biomass yield, on-farm benefits and positive externalities. A major factor limiting mallee yield is available water. Mallees are perennial plants with high water use potential and deep and laterally extensive root systems. These are adaptations to their natural low rainfall environment where evaporation can exceed rainfall by a factor of 3 to 7 and soil profiles are often deep and permeable (Wildy et al. 2004a, b; Mitchell et al. 2008; Carter & White 2009). Hence, on sloping land the preference would be for mallee belts to be arrayed on the contour in conjunction with surface water management structures to spread and help infiltrate any surface and shallow sub-surface water flows. In this way the considerable soil water deficit that develops below mallee belts can be a sink for surplus local run-off (Cooper et al. 2005; Robinson et al. 2006; Sudmeyer & Goodreid 2007; Peck et al. 2012, Mendham, in press).

Design of two-row belts in alley systems is still actively evolving (Peck et al. 2012). At present, the recommended design is for two-row belts of trees with a 2 metre side buffer and a 2 to 6 metre inter-row space to give 6 to 10 metre wide belts. Figure 4-1 shows a cross-section view of a mallee belt and adjacent competition zone. Note that this is a one-sided view and competition occurs on both sides of each belt.

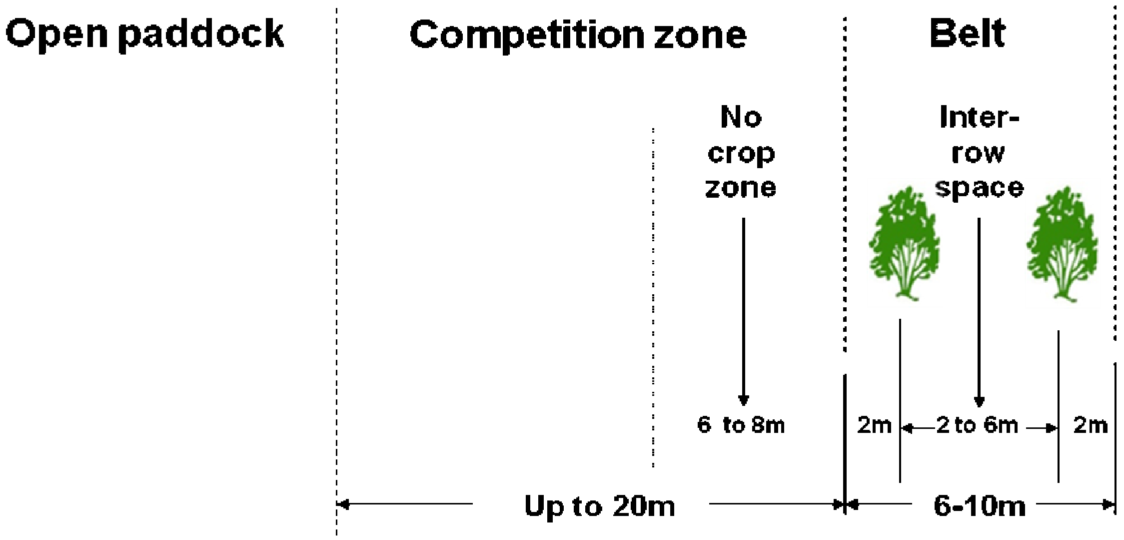

Figure 9-2 Cross-section view of a mallee belt

Tree belts need to be widely separated in order to provide the potential for generation of local run-off from the alley to facilitate intermittent recharge of the depleted soil water store beneath mallee belts, thereby maximising biomass yield potential and reducing the potential for damage that can be caused by water-logging and salinity (Cooper et al. 2004; Robinson et al. 2006; Hill et al 2005). With these design considerations in mind an inter-belt spacing of 100-150 metres is likely to be optimal. This means that belt area proportion of a typical paddock is likely to be 5% to 10% (Cooper et al. 2005, Bartle et al. 2007, Bartle & Abadi 2011, Peck et al 2012).

Two-row belts are preferred because experience with multiple-row belts (e.g. 8 rows on 2m spacing) shows strong suppression in the growth of inner rows (Peck et al. 2012). This can occur to such an extent that the yield difference between inner and outer rows may compromise efficient operation of the mallee harvester. Initially this suppression of inner rows on multi-row belts prompted the planting of two-row belts with 2 metres between the rows, to give an overall belt width of 6 metres. However the analysis by Peck et al. (2012) has shown that, because the competition zone on either side of the belt is so large (up to 2.4 times the belt area), it can be more effective in paddock-scale economic terms to increase the inter-row space in a two-row belt. Increasing the inter-row area provides more resources for the trees without increasing the cost of competition on either side of the belt. It avoids the cost of establishing inner rows, and the yield potential of the extra space accrues to the outer rows. This in turn can reduce the interval between harvests. Peck et al (2012) showed that wider two-row belts could substantially reduce the overall opportunity cost of the land influenced by the mallee belts and that this effect is more pronounced in lower rainfall areas.

Belt planting and alley farming with mallee is being developed to utilise the positive interactions between trees and wheatbelt agriculture. The purpose is to integrate mallee belts with agriculture in a cohesive and economic manner, rather than viewing them as displacing the existing agriculture. The wide dispersal of belts improves access to surplus water generated under agriculture, which helps to manage water-logging and recharge problems and simultaneously uses the surplus to improve mallee yield. Wide dispersal also provides opportunity to gain other co-benefits.

(ii) Mallee growth and biomass yield

Above ground mallee growth data for the model were derived from Peck et al. (2012). Table 9-6 shows yields for first and subsequent harvest for two-row belts with different widths (6 and 10 metres). Estimates are for the 500-600 millimetre annual rainfall zone. First harvest occurs in year 6 with subsequent harvests every 4 years.

Table 9-6 Mallee yield and harvest frequency for two different two-row belt widths

Production parameter	Unit	6 metre belt	10 metre belt
First harvest yield (in year 6)	gt/ha	58	53
2nd and subsequent harvest yield (years 10,14,18,...)	gt/ha	62	55
Average annual biomass yield over 50 years	gt/ha	14.9	13.4

Figure 9-3 charts the growth of above ground and below ground biomass according to the harvest regime given in Table 9-6 (two-row belt, 6 metre wide with 2 metre inter-row space, in the 500-600 millimetre annual rainfall zone in Western Australia). Below ground biomass (i.e. the mallee root system) is assumed to grow at a rate of 50% of above-ground biomass up to the age of first harvest (Peck et al 2012). Harvest causes loss of fine roots and slows structural root growth (Wildy et al. 2003), resulting in a rapid loss of about 20% of below-ground biomass. This takes about 2 years to be restored to the pre-harvest level. Below-ground growth is assumed to slow to a rate of 7% per year until the next harvest. Over the long term, coppice crops are assumed to continue their rebuilding of below-ground biomass after harvest, but to slow their subsequent growth of below-ground biomass from 7% per year to 0% per year after 50 years (Peck et al. 2012).

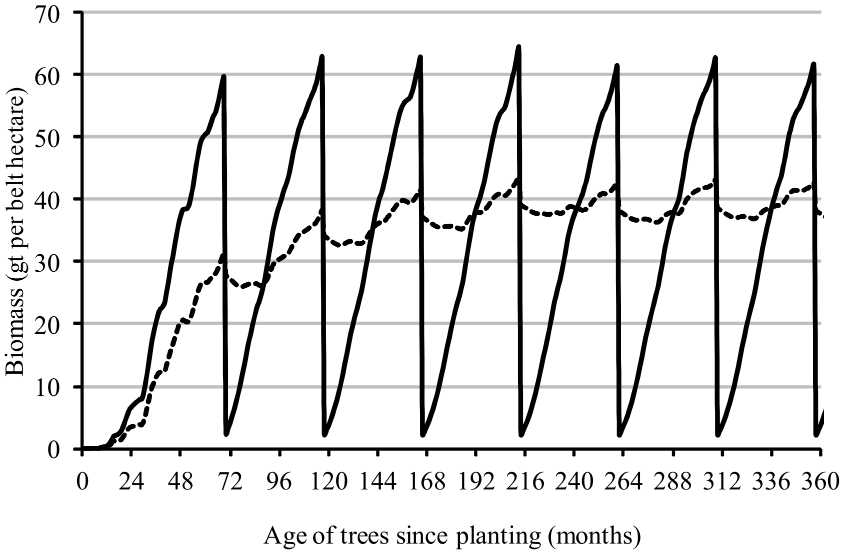

Figure 9-3 **Biomass growth above and below the ground in a harvested mallee belt**

(iii) Potential scale of mallee planting

The current lack of a market and clear price signals presents a challenge to any pro-active gearing-up of the supply of biomass as a feedstock for bioenergy. Conversely, in the future the possibility of stable, long term pricing for supplying biomass could be a positive factor in farmers' decisions to plant trees, when compared to the seasonally variable prices of grains and livestock. Farmers may also anticipate economic benefits from mallee and bioenergy industry development in the form of diversification of the farm business.

A number of co-benefits are potentially available as a complementary outcome from the use of mallee belts. Possible co-benefits include improvements for land (shelter and erosion control), water (water-logging and salinity) and biodiversity resources. Mallee plantings can also provide land managers with the option to manage farm greenhouse gas emissions. Furthermore, a mallee biomass supply chain will provide opportunities for regional industry development with increased local employment and the associated social benefits. If it was possible for mallee growers to take advantage of these benefits, through their direct or indirect economic impacts, then such potential co-benefits may well diminish the 'risk premium' that farmers might otherwise require to adopt large scale commercial planting.

The value of these complementary benefits is difficult to sharply define - many will not directly generate revenue and they may be intermittent or take some time to be realised. In spite of this they will often be a positive influence on a farmer's decision to adopt mallee planting - this is strongly indicated by the extensive adoption of exploratory planting of mallees by more than 1,000 WA farmers since 1994 (URS 2009).

On a typical farm in the Great Southern region of the south west of Western Australia the effective farm arable area is 2,400 hectares according to Planfarm-Bankwest (2012). Based on the proposed mallee planting layout, there is potential for mallee plantings of between 120 and 240 hectares on such a farm. Hill et al (2005) estimated that close to 2.1 million hectares of farm holdings are potentially suitable for sustainable annual cropping in the high rainfall (450−700 mm annual rainfall) zone of south-western Australia. Using these estimates, the potential area planted to mallees in that region could be between 105 and 210 thousand hectares. Assuming an average annual mallee biomass yield of 14 green tonnes per year there is potential for an annual mallee biomass supply of 1.5 to 3 million tonnes. Even if only a third of the suitable area is recruited to mallee biomass production the annual biomass harvest potential is between half and one million tonnes.

(iv) Competition

The land area that is economically affected by the mallee belt includes the area of the belt itself and the adjacent land (known as the competition zone). The intensity of competition declines exponentially with distance from the belt. Figure 9-1 shows the cross section dimensions of a mallee belt in an alley farming layout. Peck et al. (2012) showed that the ratio of competition zone to belt area can be up to 2.4. Especially at large ratios better profitability can be obtained by using two-row belts with a wider inter-row space. This is the reason for the variable width shown in Figure 9-1. This concept has been further developed in subsequent work by Mendham et al (in press) and was discussed in a previous section on mallee growth.

The belt width includes a 2 metre buffer on each side. The competition zone includes a no-crop zone (NCZ) of 6 to 8 metres. In the NCZ cropping width can be varied to avoid planting a crop whose revenue in that zone does not offset its variable cost of production. Beyond the NCZ, competition may still affect yield of agricultural crops but not enough to make the crop unviable. In this zone the crop has a positive gross margin (i.e. revenue exceeds variable costs) but profitability may be lower than that obtained in the open paddock. This outer part of the competition zone may extend out to 20m from the belt.

The effective total area of the competition zone varies across the mallee harvest cycle, being reduced for the first couple of years after each harvest but resuming full intensity by about the fourth year after harvest. Peck et al. (2012) show that the aggregate competition loss may be up to 8 to 10 m of land on each side of the belt, but will vary with site, time since last harvest, and amount of rainfall (higher rainfall moderates competition for water). Design and management options to minimise the competition loss are being actively developed.

Competition with adjacent farmland is modelled as a function of demand for water. The demand for water is related to standing biomass, which in turn is related to time since planting or harvest. The analysis assumes the alleys between the mallee belts are used for a three year rotation of grain crops, consisting of two cereal crops (wheat and barley) and a break crop of canola. This type of land use is common in the case study region. For convenience it is assumed that yield loss in the competition zone is a linear function of distance from the belt edge – this is a small over-estimate compared to the exponential decay of competition. The linear model is fully specified by its end points. These end points are manipulated to achieve close calibration with empirical field data. It is assumed that open paddock distance is a function of belt age with the extent increasing to a plateau over time. The extent of competition reflects root penetration into the alley, which does not increase indefinitely. Although the mallee belt is coppiced regularly, the root system remains largely intact and so the extent of competition does not change greatly after harvest. The yield loss function is used to calculate the competition cost (expressed as an area) per hectare of belt.

In the NCZ the crop yield is too low for revenue from the crop to exceed the cost of planting and harvest. Hence total yield loss is incurred in the NCZ. The width of the NCZ is varied with the harvest cycle and therefore the intensity of competition. The model used in this analysis optimises the width of the no-crop zone for each year by calculating the point at which cropping becomes profitable (i.e. where crop revenue will exceed the operating costs of cropping). This is done by estimating the income that would have been achieved in the alley, and using this to calculate the loss incurred.

It was noted in Table 9-2 that the land opportunity cost being used in this analysis (Table 9-1) differed little between the 6m ($20/green tonne) and 10m ($21/green tonne) belt widths. This analysis uses recent data from Mendham et al (in press). Using this data the opportunity cost of the competition zone is substantially lower than that reported in Peck et al (2012). The lower competition cost is due to inclusion of two additional factors in the analysis:

The first factor is the simulation of yields based on actual recorded variability in rainfall. Using variability inherent in rainfall reduces competition cost because, in wet years competition between trees and grain crops is subdued, and in the dry years the potential crop loss from competition is reduced by poor crop yield. This overcomes the bias of using average annual rainfall estimates. The bias occurs because the assumption that each growing season receives the same average rainfall locks in a high level of crop loss in every season.

The second additional factor is allowing for dynamic (seasonal) adjustment to the width of the NCZ to simulate the way a profit maximising grain grower would optimise the returns from this zone. The width of the NCZ is adjusted using predictors of likely annual grain crop revenue based on information available immediately prior to seeding – soil moisture and market trends. This calculation is a function of grain crop yield estimates based on pre-seeding rainfall and short term projections of prices for agricultural commodities. In any given season, prior to seeding of grain crops, estimates of harvest payments for major grains can be based on data provided by major trading companies such as AWB Ltd or those published by institutions such as ABARES. This information can enable a grower to make *a priori* marginal adjustment to the width of the NCZ by estimating the net returns from the land adjacent to the tree crop.

Inclusion of these two factors in the estimates of net returns from agriculture in the NCZ results in the ratio of competition zone cost to the cost of land occupied by the belt being between 1.8 and 1.3, for the 6m and 10m belt respectively, rather than 2.4 as reported in Peck et al (2012).

Other options for reducing competition cost and enhancing yield are discussed by Peck et al. (2012) and Mendham et al. (in press). For new plantings site selection can avoid areas likely to display high competition impact. For example, relatively shallow duplex soil profiles, especially where root penetrability of the subsoil clay is poor, can confine lateral mallee roots to shallow depth and enhance competition extent and magnitude. Sites with shallow saline groundwater, shallow basement rock or difficult-to-penetrate hardpan can be avoided in site selection. Furthermore, since magnitude of competition and its extent is negatively correlated with rainfall, it follows that competition cost could be reduced by favouring higher rainfall areas for new plantings.

Mallee belt systems can be designed to passively or actively capture surface water flows, which will further contribute to a reduction in competition. Another option to reduce competition is to design new plantings so that the competition zone occupies non-arable land. Such land might include farm tracks, fence lines, laneways, firebreaks, banks and drains, all linear features well suited to being aligned with long narrow mallee belts. There may also be other benefits from this. For instance since the competition zone will have reduced soil water storage and be less productive and may provide an attractive surface for tracks and firebreaks.

9.5.2 Establishment and maintenance of the mallee trees

Initial establishment of mallees in two-row belts is estimated to cost between $1,000 and $1,700 per hectare of tree belt. When this cost is divided by the total estimated biomass harvest of 830 green tonnes over a 50-year period, the cost of establishment is only $1 to $4 per green tonne. Establishment cost is therefore not a major factor in overall biomass economics. The difference between the lower and upper estimate of this item accounts for the mode of financing the upfront establishment cost.

Establishment steps include:

- Specialist advisor scopes job and inspects site to plan and design plantings
- Desktop preparation of the plan and supervision for contractor for field layout
- Contractor mark-out with laser control and digital record for mapping
- Earth works including ripping or banks for water management
- Job supervision
- Herbicide application or scalping for weed control
- Purchase of seedlings
- Despatch of seedlings to planting location
- Planting by hand or machine

Trees should be established with adequate land preparation, nutrition, and control of livestock at the vulnerable stages of seedling growth (from the winter of establishment to the following autumn) and early coppice (until shoots grow to about 50cm). With the exception of nutrient application the ongoing maintenance costs for harvested stands are small. For the lower range cost of $1,000 per hectare it is assumed that the land preparation and planting costs are minimised because the farmer carries out the operations. For the upper range cost of $1,700 land is prepared to maximise capture of surface water flows for the benefit of the trees, and contractors plant the trees.

(i) Nutrient management

Research on nutrients exported in harvested biomass by Grove et al. (2007) and Peck et al. (2012) has shown that export of the major nutrients nitrogen (N), phosphorus (P) and potassium (K) averages 50, 5 and 23 kilograms per hectare per year respectively. It is assumed that nutrient replacement will be required to maintain yields of periodically harvested mallees. Pending the results of longer term research it is assumed that N is likely to be the first nutrient to become limiting when biomass is removed through cyclical harvests. It is also assumed that full replacement cost of N removed at the rate of 50 kilograms per hectare per year is a reasonable estimate of the minimum cost of nutrient replacement for mallee belts for some decades. Replacement cost of that amount of N with urea for average mallee yield is about $3 per green tonne harvested. The maximum cost of nutrient application is set by the full cost of replacement of the N, P and K. Using appropriate fertiliser this is estimated to be about $7 per green tonne of biomass.

Although these amounts are substantial there are several factors that may delay or minimise the need for nutrient replacement practices:

- WA soils generally have a history of build up of nutrient capital. On conversion from native woodlands it was standard practice to apply large doses of the major limiting nutrients (phosphorus, calcium, sulphur and trace elements) to remedy native soil infertility, and to include nitrogen fixing legumes in the selection of crop and pasture species.
- Agricultural crops and pastures receive annual maintenance applications of nutrients and, especially in the competition zone, some of this will flow to the mallee belt to become part of the competition zone cost. This has been accounted for in the analysis.
- There is scope to modify nutrient management of annual crop and pasture to also deliver nutrients to mallee belts, for example by increasing the legume component of the agricultural rotation, or strategically applying extra fertiliser on the competition zone with the fallback that the excess is available to the mallee belt.
- Given that native mallee species are well adapted to low nutrient supply, the high initial soil nutrient storage can be safely depleted.
- The deep mallee root systems can tap nutrients stored at depth that are beyond the reach of agricultural crops and pastures, and recover leached nutrients to considerable depth in subsoil clays.

Recent research by Mendham et al (in press) has shown a substantial response to nutrients applied to a young mallee stand. This means the above assumption that passive, retrospective nutrient replacement will maintain adequate nutrition and growth needs to be reviewed. Instead it now appears that early, active nutrient application is likely to deliver a strong growth response.

The work by Mendham et al (in press) also indicates good potential to enhance water supply to mallee belts by interception of run-off and improved water use efficiency from nutrient application. Mallee belts have been shown to have strong biomass yield response to increased water supply (Carter and White 2009). It appears that this response could be enhanced by nutrient application.

The mallee genetic improvement program has intensified its focus on biomass yield and seed orchards, now established, will help to deliver this new potential. These advances in water supply, nutrition and genetics provide fertile ground for further research and promise of strong biomass yield increases. Increases in yield will provide useful reductions in biomass price. For example, a 20% increase in yield will reduce the biomass price by $6 per green tonne for a 6 metre belt system. However it is not yet clear what increase in yield might be achieved in aggregate from these improvements.

9.5.3 Harvest

Several factors influence the efficiency and cost of the biomass supply chain and while they all interact with one another, they will be considered here in terms of:

- the harvester
- the harvesting strategy
- the dispersed nature of the mallee crop
- the importance of logistics and roadside landings in the coordination of harvesting, in-field transport and road transport
- the effect of industry scale and its impact on costs in the near to medium term

(i) Harvester

The integration of two row belts of mallees with crops and livestock has evolved as a complement to a sustainable wheat belt farming system. It could be argued that mallees grown in block plantations would provide a less dispersed resource than two row belts, which could make harvesting easier and more cost effective. However, within dense block plantings (and wide, multi-row belts) competition between trees for available soil moisture typically results in low growth rates, and these reduced growth rates make it difficult for mallees to compete economically with alternative land uses.

In addition, harvesting efficiency is significantly increased by concentrating the biomass resource into fewer rows because harvesting cost is significantly reduced by increasing the mass flow rate through the machine. Trees, having large root systems, can seek resources from a much wider strip of land than the land actually occupied by the trees' stems. As a result, the productive capacity of the land in an environment with limited rainfall can be concentrated into widely spaced, discrete rows occupied by relatively few large plants per hectare of paddock. This favours the use of a machine that harvests single rows of large plants, rather than multiple rows of small plants. These mallee cropping and harvesting strategies contrast with crops like wheat, where every square metre of the paddock is occupied by many small plants, and a harvester accesses the crop as quickly as possible by using the widest front that the harvester can carry.

Since the mid-1990s it has been recognised that harvesting mallee belts would require a mobile machine that cuts and processes in a continuous stream, in contrast to a forest harvesting system that typically harvests and processes trees as individuals or in small batches. Sugar cane harvesters and forage harvesters have been used in various modified forms for coppice willow and poplar in the northern hemisphere. Initially a sugar cane harvester was trialled on the mallee in WA, but without success. From the late 1990s to the mid-2000s a first prototype mallee harvester was developed using the principles of agricultural continuous flow operation and utilising components derived from forestry harvesters and wood chippers. This harvester was only partially successful but provided fundamental experience with an agricultural/forestry hybrid machine.

The analysis of harvesting costs reported here is based on a model that represents a harvesting system comprised of a purpose-built mallee harvester that has superseded the earlier prototype. It will operate as a continuously travelling "over the row" machine that will simultaneously cut, chip and load bins towed by tractors travelling alongside the harvester. The convention adopted here is to describe the harvester as a "chipper harvester" and the in-field transport tractor-plus-bin machines as "haulouts". In this system, the harvester moves continuously to avoid the stem-by-stem nature of single stem harvesting, where the size and form of the individual stems are major determinants of the per-tonne cost of harvesting and transport (Giles & Harris 2003; McCormack et al. 2009). A prototype chipper harvester has been developed by the Future Farm Industries CRC and Biosystems Engineering based in Toowoomba, Queensland (Turnbull et al 2011).

(ii) Harvesting strategy: continuous processing and mass flow rate

For a mallee supply system to harvest and deliver biomass at the most competitive price it requires a strategy akin to those used for other bulk agricultural crops such as forage maize and sugar cane. The harvester needs to process the mallee "crop" in a continuous stream, rather than handling trees individually as occurs in forest harvesting systems where tree size is a major factor influencing the harvest cost. Because the mallee trees are small and harvested continuously, they need to be processed at the point of harvest, on the harvester, into a bulk product that is more readily transported in-field in large haulout bins. This is in contrast with common forest chip supply systems, where in-field transport is typically of either whole trees (by skidder) or logs (by forwarder), and chipping is either done at the roadside or at a centralised point.

Modelling of the proposed mallee supply chain, supported by experience in similar existing supply chains, indicates that each harvester will need to be accompanied by two haulouts that work in rotation. Ideally, the time taken for a haulout to be filled is the same as the time taken for the other haulout to travel from the harvester to the landing, transfer its load onto a road trailer or bin, and then return to the harvester. This system is described in greater detail below.

The forage harvester technique of continuous harvesting and chipping is applied in willow and poplar bioenergy crops in the northern hemisphere. In these cases modified forage or cane harvesters are used successfully under certain crop conditions. Harvesting costs as low as €15 (A$20) per green tonne have been measured in large scale trials (Spinelli et al. 2009; Spinelli et al. 2011). These levels of performance are achieved when tree crop yields are about 40 green tonnes per hectare and mass flow through the harvester (known as the “pour rate”) is up to 60 green tonnes per cutting hour. Sugar cane harvesters operate on a similar principle but chop the cane into billets rather than chips. Pour rates in the sugar industry typically exceed 100 green tonne per hour and costs for harvesting and in-field transport are currently under $10 per green tonne. These costs are the current commercial contract rates. Modelling for the study reported in this chapter has produced results consistent with these observations from the sugar industry.

The estimates for costs of harvest and haulage used in this analysis for mallees are presented in Figure 9-4. They are similar in sensitivity of per-tonne cost to pour rate to the estimates from the sugar cane Harvest Haul Model reported in Schmidt et al, 2012. Assumptions such as required power for the optimum pour rate and the capital cost of equipment are the subject of current research and development. For the purpose of this analysis an allowance is made for a 20% return on capital above cost recovery.

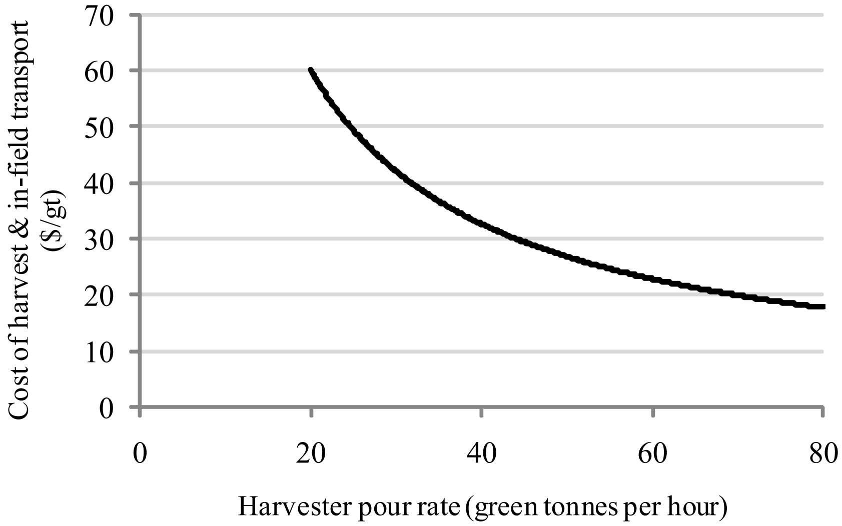

Figure 9-4 Cost of biomass delivered to roadside as a function of harvest pour rate

Figure 9-4 demonstrates that harvester pour rate is a key driver of the cost of harvesting biomass and delivering it to the roadside, where the transfer of biomass from in-field transport to road transport takes place. The non-linear shape of the cost function shown in Figure 9-4 illustrates the importance of efficient utilisation of capital and labour, and improved logistics at high pour rates where harvester and transport capacity are closely matched.

Harvesting and in-field transport requires close coordination as a single integrated system because there is no surge buffer between the harvester and the haulouts. In-field transport cost is reduced as haulout payload and speed increases, and large haulouts need to be filled quickly to maximise their efficiency. The capital cost of two large haulouts (working in rotation with one another) is similar to the cost of the associated harvester.

Increasing harvester pour rate can be achieved by travelling faster along the tree crop row and/or harvesting heavier crops. Tree harvesting is restricted in terms of harvesting speed, and experience to date suggests a harvester speed of below 4 to 5 kilometres per hour is desirable. This means that the greatest potential for high pour rates is in heavier crops. Heavier crops imply larger individual stem sizes and taller trees. The current mallee harvester can harvest larger trees than the modified forage harvesters used on willow and poplar. This new harvester technology enables the processing of trees whose sizes are between the thin stemmed willow and poplars on one hand and the typically larger single-stemmed plantation trees on the other (Table 9-7).

Table 9-7 A comparison of attributes of mallee coppice crops with willow and poplar energy crops and conventional pulpwood chip plantations

	Willow and poplar coppice crops	Mallee coppice crops	Pulpwood chip plantations
Planting density per hectare (plants per ha)	< 6,000 to >12,000	1,000 to 1,670	800 to 1,000
Planting density per km of harvester travel (plants per km)	1,500 to 4,500	500 [1]	300 to 400
Stems per plant	Mostly multi-stemmed	multi-stemmed	single stemmed
Harvest yield per hectare of tree crop area	40 gt [2]	50 to 70 gt [3]	100 to 250 gt [4]
Harvest yield per hectare of whole paddock or plantation	40 gt [2]	< 3 to 7 gt [3,6]	100 to 250 gt [4]
Harvest yield per km of harvester travel (green tonnes per km)	11 to 14 [2]	15 to 35 [3]	40 to 100 [4]
Average green biomass per plant	3 kg to 7 kg	30 to 70 kg	120 to 400 kg [5]
Tree structure	Uniform, thin flexible stems with soft wood and little side branching; heavier single-stemmed forms occur in 2-3 year old poplar.	Thicker stems, high density inflexible wood, can heavy side branching on initial harvest; some species are shrub-form.	Thick straight stems suitable for handling as logs or in bunches of whole trees.

1 The cost of seedlings and an environment with limited rainfall necessitate 2m spacing within the row to optimise biomass production.

2 Yields under reported trial conditions, Spinelli et al. (2009).

3 Mallee coppice will be grown to achieve this yield – in 3 to 5 year cycles depending on conditions.

4 Chip only, typical range for E globulus pulpwood plantations in southern mainland Australia.

5 Assuming that chip yields are two thirds of the whole tree biomass

6 The value of less than 5 green tonnes per hectare assumes that mallees are planted in belt system that occupies less than 10% of a field/paddock which is an indication of the dispersal of above ground biomass resource at the landscape scale.

(iii) Harvesting logistics for a dispersed mallee resource

The landscape in which mallees are grown is limited in its productive capacity, primarily constrained by rainfall. In these circumstances, a harvested tree crop needs to be configured so as to concentrate the productive capacity of the land into a limited number of rows of trees, so that:

- growth per kilometre of row is maximised
- the interval between harvests is minimised for cash flow purposes
- the harvester can access as much biomass as possible per hour

Yields of fewer than five tonnes per paddock hectare are typical of annual cereal and oilseed crops. However, compared with the harvested product from a woody biomass crop, the material discharged by a grain harvester is a high value, dense, homogeneous product that is almost fluid in its flow characteristics and can be handled efficiently.

The relatively low yield of mallee on a per paddock hectare basis means that a harvester operating at the optimum pour rate will range widely across large areas over periods of hours. This makes the work of the haulouts particularly challenging if they are to keep up with the harvester and simultaneously interact with road transport operations. In this system there are no stockpiles to provide any surge buffer capacity between the harvester and the haulouts. This lack of surge buffer was identified as a serious weakness by forest engineers and systems analysts (McCormack et al, 2009), who observed that the cost of interruptions in similar closely coupled systems can be high. Therefore, it is imperative that the harvester and its associated haulouts are operated as a tightly coordinated unit, always working within a narrow range of haulout transport distances between the harvester and the edge of the paddock.

It impractical to consistently drive road train trucks into paddocks to interact directly with the haulouts. The conceptual model used for this study introduces an intermediate transport step, known as a shunt, which connects the harvester's haulouts to the road transport. The shunt will be capable of paddock operations and road transport and it may be either a high speed tractor or an eight wheel drive prime mover. It will provide a flexible intermediate transport stage to link the harvester's haulouts to the road truck landings. Road trucks will be operated between local landings and the end point of biomass delivery. The landings will be suitable for all-weather use by road trains and be spaced at about 20 km intervals.

The transport system will thus be operated at three levels to provide enough flexibility to function reliably under variable conditions:

The two in-field haulouts will be closely associated with the harvester and restricted to short transport distances of about two to three kilometres. Biomass will be delivered to the paddock gate and stockpiled for short periods in bins, providing a small surge buffer. The time scale for coordination within this harvest/haul operation will be measured in minutes.

A shunt transport step will transfer the biomass from the paddock gate to the landing, a distance of up to approximately ten kilometres. This stage only needs to coordinate with the harvest/haul stage over periods of hours due to the small surge buffer at the paddock gate.

Road transport, utilising conventional prime movers and trailers, will collect biomass from the landings where bins or trailers have been assembled by the shunt operation. This surge buffer at the landings would be relatively large, so coordination with the shunt would only need to occur over a time scale of shifts or days.

(iv) Industry development and its effect on costs

Research and development is in progress to identify ways to maximise mallee productivity through genetic improvement, better nutrition, belt design and surface water management systems. .

There is no commercial harvesting of mallees at present, and the supply chain is only partially developed, with much of it only at the conceptual design stage. There is significant potential for reducing the cost of delivered biomass through technical development and refining procedures with operational experience. Aside from the outstanding technical issues, cost reduction and efficiency will primarily be influenced by industry scale and the spatial distribution of the biomass resource.

The existing mallee resource, planted by farmers located primarily in the wheatbelt of WA, is widely dispersed and covers a wide range of ages. Within a 100 km radius of any point, there would probably be less than 50,000 green tonnes available for sustainable supply, but this has not been reliably quantified. An indicative commercial scale biofuels plant could require 150,000 tonnes per year of biomass with 10% moisture (Colin Stucley pers. comm.). This would require a total mallee resource of 245,000 green tonnes per year of mallee at 45% moisture. It will take around 6-7 years to bring a new resource of this size from initial planning to first delivery of biomass.

Table 9-8 summarises the principal features of a mallee industry that will improve in efficiency, leading to cost reductions, as the flow of biomass increases. Cost reductions achieved by increasing the size of the resource and the industry are expected to be the result of:

- Improved utilisation of machinery due to increased mallee resource leading to greater annual tonnage throughput and better utilisation of capital
- Locating the new mallee resources close to markets to reduce transport costs
- Increasing the density of planting around landings to reduce the inefficiency of frequent relocation
- Experience with the supply chain, leading to improved coordination and better logistics, and higher levels of machinery utilisation, also known as field efficiency
- Technological advances in harvesting, development of better haulouts for in-field transport and development of road transport systems that minimise loading and unloading times (terminal time) for each load.

Table 9-8 Anticipated changes to major variables with industry development

Harvest and haulage scenario	New developing industry	Mature industry
Annual green tonnes per harvester	25,000 to 50,000	75,000 to 120,000
Harvester pour rate (gt/h) [1]	50 - 60	60 - 75
Plantings – location & design	Small sites common; sites often widely dispersed making logistics complex.	Sites larger and grouped in clusters to improve logistics of in-field operations.
Distance of plantings to processor	Up to 150km road distance to access existing resources. 250km may be necessary during market development trials.	Less than 100km road distance[2] for resources established around centralised processing facilities.

1 As discussed in preceding sections, pour rate is a critical factor. The existing prototype harvester has achieved 35 green tonne per hour and is limited primarily by the available power installed in the machine. Subsequent prototypes will have greater power, and with experience and refinement, should be able to achieve pour rates up to 75 green tonnes per hour.

2 To supply about 245,000 tonnes per year, farmer recruitment and the proportion of land that each landholder is willing to dedicate to mallee plantings needs to be realistically considered in light of profitability of mallees relative to other land uses.

It is anticipated that as the industry *starts* at about 20,000 – 30,000 green tonnes per year, a harvester will operate at full capacity for whole days at a time. Under this harvesting strategy the means by which the annual tonnage is varied will be by harvesting in short campaigns. This is because some variable costs are effectively fixed costs per day or per week. For example, a skilled plant operator will expect to work for an entire day and preferably weeks at a time. In addition contract trucks can only work at a competitive rate when engaged for whole weeks, rather than hour by hour.

Table 9-9 presents the results of modelling biomass supply chain costs under a range of industry scales. There are many assumptions in this modelling, made with reference to past analyses (Giles & Harris 2003; McCormack et al. 2009) and also recent work by the Department of Environment and Conservation WA and the National Centre for Engineering in Agriculture (Schmidt et al 2012).

Table 9-9 The effects of industry scale and harvester pour rate on cost of harvesting and in-field transport

Scale of industry		Near future		Mature		
		lower range	upper range	lower range	mid-range	upper range
Annual tonnage	gt/year[3]	25,000	50,000	75,000	100,000	120,000
Harvester pour rate[1]	gt/h[3]	50	60	60	70	75
Days of operation	days/year	80	135	200	235	235
Cost to roadside	$/gt[3]	$34	$25	$23	$20	$19
Cost plus profit [1]	$/gt[3]	$57	$37	$31	$26	$24

1 Mass flow rate per hour of cutting, which excludes maintenance, waiting, turning and travelling.

2 As an approximation of a contractor's price, a profit equivalent to 20% of total capital invested for the required equipment is added to the estimated costs of ownership. It may be possible to reduce the capital in "near future" scenarios by using second hand machinery and seeking public industry development support for high value capital items.

3 gt = green tonnes harvested per year per harvester

The breakdown of the "mature industry mid-range" scenario in Table 9-10below demonstrates that capital is a very significant cost. The estimated costs of capital for new equipment used for all the harvest and haulage scenarios were close to $3 million. As described in the logistics section above, this industry is not the same as grain, forestry or sugar, so supply chain operations need to be a combination of existing and new methods that will achieve the efficiency required.

Table 9-10 Costs of harvest and haulage associated with a mid-range scale of operation in which each harvester processes 100,000 green tonnes

Cost category	Costs and their sources ($/green tonne)				Perc.
	Harvest	Haulout transport	Shunt transport	Total at roadside	
Fixed annual costs incl. capital	2.90	2.90	1.40	7.20	36%
Fuel	2.40	1.70	0.90	5.00	25%
Repairs & maintenance, chipper knives, tracks/tyres	2.10	0.70	0.30	3.10	16%
Wages	1.20	2.30	1.20	4.70	23%
Totals (not including profit)	8.60	7.60	3.80	20.00	

9.5.4 Road transport

The transport costs for bulk commodities from existing industries such as wood chip and wheat offer a guide for cost of road transport for mallee biomass. The product that most resembles mallee biomass (i.e. wood chip) is expensive to transport when compared to bulk commodities such as grain. The industry standard costs per tonne per kilometre are about $0.10 to $0.12 for grain and about $0.17 for pulp wood chip in WA. These estimates are the average of values quoted by several commercial trucking firms that were contacted by the authors.

Both grain and wood chip are transported in rear-tipping bulk bin trailers with the same payloads in the same basic road train configuration. The range of observed values illustrates why it is difficult to simply adopt the costs experienced by existing industries for the purposes of projecting future costs for mallee. As the mallee industry will be one of small margins, it needs the cost structure of grain transport but it is transporting a material more like wood chip.

The difference in the cost of transport of different bulk commodities is largely due to the terminal time (the time taken to load and unload each truck) imposed upon each system by characteristics of the transported material, other components of the supply chain, and historical factors. Grain terminal times are relatively short and the trailers do not need to be uncoupled for loading or unloading. Wood chip terminal times are typically longer than for grain for reasons discussed below.

(i) Characteristics of the material

Grain is almost fluid in its flow characteristics, so trucks can be filled from overhead hoppers or high capacity augers and pneumatic conveyors. When unloading, grain flows over trailer drawbars and through grizzly screens into pits, so tipping the front trailer does not require uncoupling of the back trailer.

Wood chip is prone to bridging and will not flow unassisted through a grizzly screen. Trailers must be tipped into an open pit, or onto the ground for reclaiming by a loader (at additional cost). As the front trailer cannot tip unless the back trailer is uncoupled, unloading is a relatively long process. Whole tree biomass contains twigs with leaves attached, so the material bridges more readily, and is likely to be more difficult to unload than clean wood chip.

(ii) Other supply chain components

It is common practice for grain to be transported from the farm to the local wheat-bin (a shared bulk handling facility) by a wide variety of farmer-owned and operated trucks, and this transport step is difficult to cost or compare to a future mallee harvesting operation. The industry costs of $0.10 to $0.12 per tonne per kilometre relate to transport either from the local wheat-bin, where large-scale loading infrastructure is well developed, or from large farms direct to port. Loading is rapid and port facilities to receive the grain take advantage of the characteristics of grain to enable rapid tipping of multiple trailer trucks.

Wood chip transported from the plantation to port involves loading the trucks with the roadside chipper, and the process rate is determined by the chipper, which is the largest, most complex, and most expensive item in the supply chain. As the rate determining step, chipping fixes the truck loading time at about 40 minutes. Keeping the chipper operating continuously is the highest priority and it is preferable to have a queue of trucks than an idle chipper. For historical reasons unloading commonly takes a similar period of time.

(iii) Historical factors

- For grain, the transition from single trailers to road trains has had little impact as grizzly screens have been used since the advent of bulk handling. Loading has always been over the side, and high-capacity augers and pneumatic conveyors minimise loading time.
- Some sugar regions in Queensland adopted side tipping B double road transport from the outset, but other regions have had to evaluate a change from single semis to B double trucks. In the NSW region (three mills owned by a farmer cooperative, processing 1.5 to 2 million tonnes of cane per six month season) the cost of converting the receival pits at the mills was determined to

be too great to justify the change to side-tipping B doubles. The truck fleet is operated by the mill cooperative, so the owners of the supply chain would have benefited from any improvements - this is an example of a system caught by historical factors. The mills have placed a strong emphasis upon minimising terminal times, using sophisticated GPS-based software to coordinate collections from several harvesters and carefully regulating the arrivals of trucks at the mills to avoid queuing.

- In the wood chip industry there is a similar historical trap. The ownership structure is complex with transport operations owned by a wide variety of businesses. Receival facilities are commonly owned by other parties and take deliveries from all the transport operations in the surrounding region. The industry was established with single-trailer trucks discharging out the rear by variety of means, and with the complexity of ownership even new trailers and infrastructure are forced to comply with the status quo. In addition, many of the participants in the system have no commercial incentive to change because any inefficiency is ultimately paid for by the plantation owners via reduced stumpage. Wood chip road trains are therefore broken up each time they are unloaded, which combined with the need to fill trucks with chippers, means transport costs are relatively high.

The mallee biomass industry is starting without the legacy of established practices and so there is an opportunity to pick the best characteristics of the diverse range of existing systems and design an operation that minimises terminal times and hence operating cost. This also means that anticipated costs reported here are derived from models rather than benchmarks from established bulk transport industries.

In the attempt to minimise transport costs of biomass for bioenergy, a common concern is the influence of bulk density, but for green biomass bulk density may not be a problem with appropriate system design. The use of chip trucks for the transport of whole tree mallee biomass has demonstrated that bulk density for settled biomass is in the range of 350 to 400 kilograms per cubic metre, which is very similar to the values experienced by the wood chip transport industry. The road train configuration for transport of green woodchip results in a payload of 50 to 55 green tonnes. Bulk density will be a significant concern if dry chipped biomass is transported. Because of the difficulty of settling dry biomass in a bin, it is possible that dry biomass loaded to maximum trailer volume may contain less dry matter than green biomass which tends to settle under its own weight. This effect has been noted in the loading of ships that transport woodchips.

Recent trials with chipper harvesting combined with sugar cane haulouts indicates that pouring green biomass from bin to bin can be achieved without significant loss of bulk density. This means that sugar cane machinery, perhaps with only minor modifications, can be used in the mallee operations. More extensive field trials are proposed after the construction of the first commercial-scale harvester.

The mallee transport costs presented here are derived from first principles, calibrated by standard industry rates. Modelling results presented in Figure 9-5 and Figure 9-6 show the difference between long and short terminal times per load of biomass. The costs for the longer terminal times are calibrated using wood chip transport industry benchmarks and the short terminal time scenario is based on grain transport costs.

Figure 9-5 describes the anticipated relationship between haul distance and the cost of transport. Transport distance has smaller influence on cost per tonne for distances less than 50 kilometres when compared with distances above 100 kilometres. This is caused by the increasing proportion of time per load spent in terminal time and reduced average speed for short hauls. There is a reduction of $4 per tonne for a reduction of an hour in terminal time.

Figure 9-6 describes the relationship between cost per tonne and distance on a per kilometre basis. It shows that, for biomass transported over short distances, the increasing proportion of terminal time and reduced average speed substantially increase the cost per tonne per kilometre. For trips longer than 100 kilometres the marginal cost of additional haul distance reduces to $0.10 per tonne per kilometre. This is close to minimum rates for haulage in the grain industry resulting from a combination of efficiencies in terminal time and long distances.

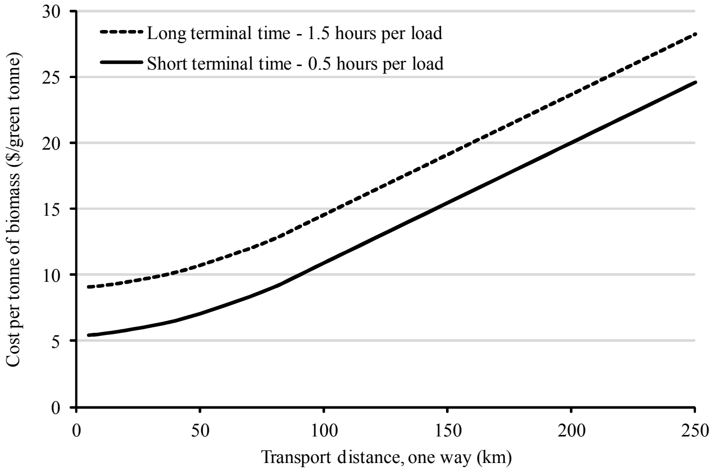

Figure 9-5 Transport cost per tonne of mallee biomass for two load/unload scenarios

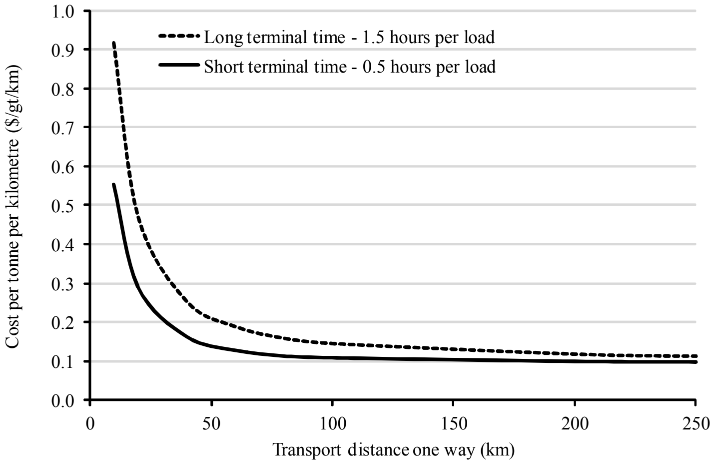

Figure 9-6 Mallee biomass transport cost per tonne per kilometre for two load/unload scenarios

With a purpose-built transport system that avoids the need to break up and re-assemble road trains it is expected that road transport will cost between a minimum of $5 per tonne for very short hauls and about $15 per tonne for a 140 km distance, as shown in Table 9-11. These estimates are obtained from analysis using the transport model specifically developed for the mallee biomass industry. A more detailed discussion of the method for estimating transport distance for a whole feedstock collection area is presented in Yu et al. (2009).

Table 9-11 Estimated road transport costs for mallee biomass

Road transport distance one way	15 km	70 km
Radial distance	10 km	50 km
Cost per green tonne	$5	$9

9.5.5 Supply chain management and administration

Table 9-12 shows the costs associated with setting up and maintaining administrative systems for an effective supply chain system. The costs were obtained from commercial real estate industry sources for office space in a regional town and current remuneration rates and standard wages for staff and the attendant operating costs and on-costs such superannuation, and similar overheads per employee.
The cost structure assumes an administrative system functioning such that:

- appropriate farm land with suitable soils and rainfall is identified close to the processor
- landholders are recruited, contracts are drawn up and managed for establishing, growing, harvesting and delivering biomass
- biomass growth, and potentially carbon sequestration rates, are monitored, audited and reported
- timely payments are made for biomass;
- quality control is carried out
- harvest regime is optimised for tree vigour and security of supply

Table 9-12 Cost of management and administration of mallee biomass supply chain

Time frame	Biomass volume traded (kt/year)	Office space required (square metres)	Office lease cost ($/year)	Staff wages & operating costs ($/year)	Cost per unit of biomass ($/gt)
Small emerging industry	25 to 50	55	13,200	150,500	6.00
Mature industry	200 to 300	78	18,720	890,000	4.00

The cost range of $4 to $6 per green tonne of biomass assumes a transition from a small emerging mallee biomass industry ($6/gt) which requires less capital and labour to manage the biomass trade (25,000 to 50,000 green tonnes), compared with a mature, and more efficient industry ($4/gt), which requires supply chain management and administration for the trade of 200,000 to 300,000 tonnes of mallee biomass. It is assumed that, in keeping with experience in other bulk trading industries, economies of scale will emerge over time to reduce the marginal administrative cost of additional tonnes of biomass.

9.6 Revenue and benefits of biomass production systems

9.6.1 Biomass sales

The price paid for biomass must necessarily reflect the cost of establishment of the trees, the costs of growing the biomass, its harvest, haulage and finally the delivery of the chipped biomass to the buyer or the user. Table 9-1 shows that, depending on a variety of factors, the delivered costs of mallee biomass (or the processor gate price) may be between $53 and $70 per green tonne. About 35% of the price is to compensate the landholder for the land occupied by the trees and the competition they impose on adjacent agricultural crop. A similar proportion is required for harvest and haulage.

If land-owners are also the mallee growers, then they are likely to consider by the co-benefits of tree belts. These include the aesthetic and possible land value benefits of adding trees to the landscape including any credits that may be paid for carbon sequestered by the trees, protection for livestock and prevention of wind erosion, reduced water-logging and lower rate of salinisation.

Farmers may also anticipate economic benefits from mallee and bioenergy industry development in the form of diversification of the farm business, options to manage farm carbon emissions, and regional industry creation with increased local employment and other social benefits. These potential benefits, coupled with increased biodiversity and off-farm benefits may encourage many landholders to pro-actively plant mallee belts.

In Australia, there is no market information available for traded woody biomass from coppice tree crops grown on farms. However, some indications of international biomass prices are available. A review of the economics of biomass feedstocks in the United States (BRDI, 2008) concluded that high establishment costs and lack of efficient mechanical harvesting techniques for woody crops were significant factors in cost of production. The estimate of the delivered price for short cycle woody crops was around $A3 per gigajoule or about $A57 per tonne of dry biomass, which is about A$31 per tonne for green biomass containing 45% moisture. IEA (2011) reported a cost of €70 per dry tonne (about A$45 per green tonne containing 45% moisture) of woody biomass supplied to European processors. They estimated that at this biomass price it would be possible to integrate fast pyrolysis units into pulp and paper milling systems to replace fossil fuels.

Large volumes of wastes are available from Australian forestry operations, such as clear-fell residues from bluegum pulpwood harvesting. These materials appear to be traded in the vicinity of $50 to $60 per delivered semi-dried tonne. However, the delivered prices for these residues, which are mixtures of foliage, bark and small wood, also tend to be the combined cost of collecting, processing and transporting the material. Some plantation owners prefer to keep this harvesting trash on site for its nutrient value rather than accept the modest payments offered for the material in the plantation (Stupak et al 2007). The residues from commercial forestry activities may be contaminated with soil because they are sourced from piles of woody trash left behind after removal of logs. Soil contamination reduces the value of the biomass because of its negative impact on the equipment in the processing plant.

Another source of lignocellulosic biomass is cereal straw. There is potential for cost reduction in harvest and supply chain services with long-term contracts, technical development and scale. Direct comparison between prices of baled cereal straw and mallee biomass is of limited value due to the moisture content and the performance of the material in the biomass conversion process. The current price for straw reflects its value to the livestock industry, where it is used for bedding of domesticated animals and also as filler in livestock feed mixes (Ann Noakes of Glenbraewa, Narrogin pers. comm., 15 October 2011; Steve Blacker from Logan Contracting pers. comm., 15 October 2011; Rodriguez et al. 2011). Between the 2002 and 2008 seasons, the average annual indicator price of cereal straw was around $100 per tonne delivered (Martin, 2009).

Up to 35% of the cost of mallee biomass is compensation to the landholder for the land planted to trees and competition with other crops, so the major determinant of biomass cost will be biomass yield. Yield is influenced by site selection, planting configuration and water supply. These variables are fixed at establishment and are therefore permanent determinants of yield. Better choice of settings for these variables is a major focus of current R&D.

Sensitivity analysis with the model used for this study shows that a 20% improvement in yield can achieve a reduction of $6 per green tonne in the cost of delivered biomass. In a series of 18 long term experiments on harvest regimes, (Peck et al., 2012) yield differences larger than fourfold were observed within and between experimental sites. Hence there is plenty of field variation to work on in order to achieve a 10 percent higher average yield with improved site selection technique. Furthermore, there is good potential to increase yields with technical improvements in genetics, nutrition and water management.

Peck et al. (2012) used an empirical analysis of water use efficiency which suggested that the best performing sites had access to water sources in addition to rainfall, and that poor performing sites had soil profile constraints. They concluded that high local variability in yield would make site selection difficult. They suggested that dispersal of belts would discriminate against conventional ground-based techniques of site selection and favour development of new remote sensing and spatial data analysis methods. Their results indicate that site selection and water harvest should be closely linked in planning and design of new plantings.

Peck et al. (2012) also showed that belt configuration is a key determinant of yield. A tree belt can be designed with layout across slopes such that it will maximise interception of lateral water movement. This layout, coupled with active forms of water harvest, has the potential to improve biomass growth and harvest yield. Mendham et al (in press) also explore yield and layout design. This is discussed in section 9.6.3.

9.6.2 Carbon revenues

It is possible that tree belt plantings will satisfy the rules of the Carbon Farming Initiative (CFI) legislation of the Australian Government (DCCEE, 2011) and thus generate revenues from sequestering carbon. Because the opportunity for mallees within the CFI is not yet finalised, the sequestration revenue estimated in this study is only indicative.

The CFI is an instrument for encouraging greenhouse gas abatement in the rural sector. It is designed to provide the agricultural and forestry sectors with incentives for reduction of emissions and for sequestration. Landholders would submit projects for approval on a voluntary basis. Offset credits from a range of approved activities may be sold by landholders, so long as legal obligations such as periodic reporting are met. Under the CFI, offset credits from biosequestration will be based on the net emissions or removals each year as measured against a baseline. The baseline represents the emissions that would have occurred in the absence of the incentive provided by the CFI (DCCEE 2011).

The CFI incorporates standards to deal with additionality, permanence, leakage, measurement and verification (DCCEE 2011). Activities that generate GHG benefits would not be considered additional if they were financially viable without a carbon price, had already been funded under government programs, or were required under regulation. Financial additionality is a complex issue (Garnaut 2011). Under the CFI legislation, carbon payments may be based on total projected net greenhouse gas removals over the period of scheme obligations, less a risk of reversal buffer. If coppice harvested mallee planting qualifies as a positive carbon sequestration activity and is included on the positive list of CFI then the owners of the trees will be able to receive credits via participation in the CFI scheme.

Garnaut (2011) pointed out that under the CFI the quantity of emissions and sequestration will vary with natural disturbances or changes in land use, and also with the fluctuations of business activity. For instance, when forests are grown for harvest, carbon sequestration occurs until harvesting takes place. There is then a loss of carbon followed by further carbon sequestration in new growth. Unnecessary transaction costs could be avoided by averaging the emissions and removals for each forest stand over time, and issuing credits and requiring acquittal of liabilities on this basis.

In this study, carbon payments were calculated according to the endpoint averaging system in recognition of the fact that harvested biomass crops from mallee will experience not only significant periodic loss of stored carbon from harvest but also variation due to fluctuation in rainfall (DCCEE 2010). The end point averaging calculations were applied to the amount of below and above ground biomass less the amount of biomass harvested six years after planting and thereafter every four years (see Figure 9-3). The carbon price is assumed to start at \$23/t of CO2-e and rise by 2.5% per year. The estimates for carbon sequestered in the harvested trees include a 5% risk of reversal buffer. Carbon revenue of harvested mallee belts is estimated to be \$1,805 per hectare of trees (undiscounted) over a 50 year period, equivalent to \$2.17 per tonne of biomass (Table 9-13).

Table 9-13 Potential sequestration of carbon in coppice harvested mallee belts and the revenues associated with carbon credits estimated over the 50-year life of the mallee plantation

Tree age (years)	1	2	3	4	5	6	7	8+	Total	Units
Carbon stock change	13.8	13.8	13.8	13.8	13.8	3.1	0.0	0.0	72	t CO2-e /ha
Carbon income	327	336	344	353	361	84	0	0	1,805	\$/ha
Tonnes of CO2-e sequestered per tonne of biomass harvested									0.09	t CO2-e / gt
Carbon revenue per tonne of biomass harvested									2.17	\$/gt

It is emphasised that the CFI eligibility of harvested mallee belts is still being assessed. The results for carbon revenues reported here are presented to indicate the relative size of the revenues and the stream of payments that are likely in the event of harvested belt planting qualifying under the CFI.

9.6.3 Water-logging and reduction of recharge

Transient surface and shallow sub-surface water-logging is a major cause of reduced annual crop yields in Western Australia, especially on duplex soil profiles in the higher rainfall areas where rainfall exceeds 450 millimetres per year on average (Gregory et al. 1992; Cox & McFarlane 1995; Hill et al. 2005). Hill et al. (2005) show that if growing season rainfall is greater than 350 millimetres, water-logging causes loss of about 40% of crop yield potential in the high rainfall cropping zone of the south west of Western Australia. They proposed indicators of water-logging risk based on slope and amount of winter rainfall in excess of potential evapo-transpiration. They developed water-logging risk maps for years where rainfall was low, medium or high. They advocate drains as the best treatment for sloping areas subject to water-logging but noted that other agronomic methods are also useful.

Open surface drains have been used successfully in WA to intercept and divert surface and shallow sub-surface water from sloping land in order to relieve water-logging (McFarlane & Cox 1992; Moore & McFarlane 1998). This can be economically attractive, in spite of the cost of land withdrawn from production (drain width is up to 8 metres) and the cost of safe disposal of diverted water (McFarlane & Cox 1992). Drains are most commonly low-profile banks with a low gradient along the drain and discharge into a constructed waterway to flow downhill without causing erosion.

Belts of trees can be designed to perform the function of drains in order to intercept both surface and shallow subsurface flows and thereby relieve water-logging (White et al. 2002, Silberstein et al. 2002, Ellis et al. 2006 & 2007, Ellis & van Dijk 2009). Ellis et al. (2006) showed that under simulated intense, short duration rainfall events a tree belt captured a significant proportion of surface run-off, reflecting its higher infiltration rate compared to adjacent pasture. The elevated infiltration rate was related to the initially drier soil under the trees, the presence of open macropores at the soil surface, surface litter and absence of grazing. They concluded that the additional water could also have significant implications for the productivity of the tree belt.

Robinson et al. (2006) and Sudmeyer and Goodreid (2007) reported that the depletion of the historic accumulation of soil water under the prior agriculture by mallee belts (aged 4 to 7 years) at several sites ranged up to 1,800 mm over the maximum depth of investigation of 10 metres. Robinson et al. (2005) also showed that the lateral extent of soil water deficits could extend 20 metres from the tree belt. A soil water deficit of 1,000 mm over the full cross sectional area of the water depleted zone (20 metres on each side of the belt and a maximum of 10 metres deep) indicates a potential soil water sink of around 20 megalitres per kilometre of belt. This is ten times greater than the maximum annual flows of interceptor drains observed by McFarlane and Cox (1992) in regions with higher than 450 millimetre of annual rainfall in Western Australia. Hence there is potential to divert all likely intercepted water into storage beneath mallee belts on sloping land and avoid the need for disposal.

Ellis et al. (2006) relied on the natural features of tree belts to facilitate infiltration under intense rainfall events but achieved only partial capture. To ensure that a high proportion of water intercepted on slopes can be infiltrated into storage it may be necessary to complement the natural features of the belt with detention storage, probably in the form of low gradient banks to also spread water along the belts to even-up the beneficial effects of extra water supply on biomass production.

In the analysis reported in this chapter the value of the avoided water-logging loss from a contour-aligned configuration of mallee has been estimated. It is assumed that mallees are planted on sloping land with suitable soil types in two row (6-10 metre wide) belts at an inter-belt spacing of 100 metres with a competition (high water deficit) zone width of 20 metres each side of the belt. It is also assumed that in high rainfall years (1 in 3), when the probability of water-logging is high, protection from water-logging is provided to 5 metres (lower end of range) and 35 metres (upper end of range) of width beyond the competition zone. The belts capture all surface and shallow sub-surface run-off and thereby prevent any expression of water-logging over these widths on the soils defined by Hill et al. (2005) as being prone to water-logging. Such soils were assumed to be cropped in 50% of years. With these inputs the analysis showed that the value of additional crop yield resulting from amelioration of water-logging was about $10 per green tonne of mallee biomass (upper end of the range), and $1 per green tonne (lower end of the range).

This analysis dealt only with water-logging control in crops as an external value of biomass production expressed in revenue per green tonne of biomass. It does not include valuation of any mallee yield gain that may result from more efficient capture of run-off, nor does it account for the reduced intensity of competition in wet years (Peck et al. 2012). Furthermore, the other collateral benefits of water-logging control listed by McFarlane and Cox (1992) and Moore and McFarlane (1998) are not included in the valuation. These benefits include moderation of groundwater recharge, water erosion, flooding, wind erosion and soil structure decline. Some of these benefits have been quantified elsewhere in this chapter. These problems may be intermittent or only manifest in the long term and the assessment of the physical damage and cost is difficult. Better water-logging control would facilitate adoption of a higher proportion of cropping in the rotation, i.e. up from about 20 percent of farm in crop to 50 percent (Hill et al. 2005; Planfarm-Bankwest 2012).

The large potential soil water sink that could be generated by mallee belts on favourable sites opens the prospect that water harvest from sites not suitable for planting could be undertaken, i.e. water could be systematically harvested from unsuitable sites and channelled (using low-cost structures) to adjacent areas with suitable soil types where it would be infiltrated along mallee belts. This adds another option to the objective of planning water sources and sinks on sloping land, as proposed by Ellis et al. (2007). It extends the relevance of the concept of mimicry of native ecosystems to a higher level (Nulsen et al. 1987; Lefroy et al. 1999; Tongway et al. 2001; Mitchell et al. 2008). In particular, it indicates that classification of sites for suitability as sources or sinks based on native ecosystem attributes is likely to be a useful capability for site selection and design of belt systems.

9.6.4 Shelter and protection

Belts of trees can act as windbreaks and deliver benefits to agriculture. These benefits can be discussed in two categories. The first is moderation of local climate and biology such that downwind plant productivity and land stability is improved (Nuberg 1998; Cleugh et al. 2002; Nuberg & Bennell 2009). The second is provision of shelter for stock, especially during extreme weather or at lambing and shearing when stock are especially vulnerable (Reid 2009).

(i) Moderation of wind exposure for land and crops

Plant and land benefits occur in the more benign microclimate immediately downwind of tree belts. The reduction of wind speed extends for up to 20 times the tree height. This is associated with a less extensive zone of reduced evaporation with higher daytime and lower night-time temperatures. These conditions are generally more favourable for plant growth and farm operations, but are especially beneficial during weather extremes. Plants benefit through reduced water use, warmer winter daytime temperatures, and better conditions for pollination and seed set. Farm management can take advantage of shelter, which reduces risk and provides flexibility in scheduling field operations. For example, infrequent weather extremes bring short duration, high-risk conditions where mechanical damage and wind erosion can occur. Crops can be flattened and stems broken. Sandy soils are prone to sandblasting of emerging crops or pastures and wind erosion can degrade soils.

Shelter benefits can be variable over time, season, crop type, soil type and belt attributes. Cleugh (2003) reported on crop yield simulations using the APSIM model applied to data generated in the National Windbreaks Program. Cleugh’s report showed, with simulations using long term weather records averaged over 20 years, that shelter benefits were always positive with the largest gains around 20 per cent. Sudmeyer et al. (2002) measured shelter benefits at regular distances from the windbreak for 74 ‘site-years’ over the period 1988-97 in the Esperance region in Western Australia. They found that the net yield in the sheltered zone between 1 and 20 tree heights was little different from the unsheltered yield. However, the net yield includes the zone from 1 to 4 tree heights from the windbreak where crop suppression was observed. In other words, the zone from 5 to 20 tree heights showed a small increase in yield. The response to shelter was stronger in years of low rainfall or severe wind erosion. Bennell & Verbyla (2008) used harvest yield monitoring equipment to measure shelter benefits on large plots at 32 sites in the period 1997 to 2000. They found responses in the yield benefit zone averaged 3.7% for cereals (over a distance of 2.2 to 9.7 tree heights) to 14% for pulses (over a distance of 1.7 to 10.4 tree heights). However, a major conclusion of the National Windbreaks Program was that, after accounting for costs of establishment, occupation of land (including the competition zone) and crop yield gain, economic benefits of windbreaks are small or cost neutral (Cleugh et al. 2002).

The low height and regular harvest regime of mallee belts makes them less effective than taller, unharvested trees in providing shelter for crops and land. Furthermore, the farmer is likely to prefer to conduct cropping in the early years after harvest when the competition zone is subdued, and may choose to switch to grazing in the later years when the belt is taller and crop competition is more intense (Peck et al. 2012).

On the other hand, if the commercial development objective of mallees is realised, all costs will be covered and any shelter benefit will come without cost. However, the conclusion of Nuberg and Bennell (2009) from a review of the Australian experience with shelter is probably valid for mallee belts - that the shelter benefits conferred on crops and land will only be significant on erosion prone soils, where pulse crops are grown or as background insurance against the most extreme weather events. It is concluded that crop shelter benefits from mallee belts will be variable across sites, but generally small and difficult to quantify.

(ii) Shelter for livestock

Studies of shelter for livestock have shown that adverse weather conditions create life-threatening conditions for lambs, even at moderate temperatures. Lamb deaths are an animal welfare problem as well as an economic loss to graziers. Pollard (2006) reported that wet, cold, windy weather added 38 to 76 percent to mortality rates. Wind shelter has been found to reduce mortality rates of single lambs by 3 to 13 percent. Reduced death rates of 14 to 37 percent have been reported among twin lambs.

For tree belts to be effective as shelter, they would have to protect lambs from wind, rain, radiative and conductive heat loss, as well as allowing lambs exposure to the sun. Shelter should be familiar to livestock and well dispersed to encourage ewes to isolate themselves from other sheep at lambing. Coppiced mallee belts, which produce dense hedges, are very likely to increase lamb survival and possibly growth. Mallee tree belts have the advantage of providing valuable shelter as an additional benefit when they are planted primarily for commercial production of biomass. This would avoid the commonly observed lack of economic incentive and means of planting shelter belts dedicated principally for protection of neonatal lambs.

A recent study by Robertson et al. (2011) considered whether provision of shelter in the form of tree belts could increase survival of lambs compared with unsheltered paddocks. They found that tree belts can form a ‘maternity ward’, which can improve survival rates especially of twin lambs. They reported that in the absence of shelter around 20% of lambs die in the perinatal period and that this could be considerably higher for twin lambs.

In the study reported in this chapter, the estimation of economic benefits of improved lamb survival attributable to shelter provided by mallee tree belts included the following factors:

- Average winter grazing stocking rates at 4.5 Dry Sheep Equivalent (DSE) per hectare
- The average net profit from sheep flock at $12 per DSE
- Lambing percentage of a typical farm at 85%
- Number of ewes per flock - averaged over several years and assumed to be 2,000
- Income from lambs per farm at about $14 per DSE
- Proportion of years in which lamb losses occur due to lack of shelter. For the lower estimate this was assumed to be 40%. For the higher estimate this was assumed to be 80%
- Proportion of lambs that are lost due to lack of shelter, assumed to be 40%
- Loss of lamb trading income from the sheep enterprise due to lack of shelter was estimated to be $5,840 per year for the lower estimate and $11,680 per year for the higher estimate

- Number of trees required for shelter was set at 100 trees per ewe for the lower estimate and 200 trees per ewe for the upper estimate
- Mallee belt layout was 6 metre wide for the lower estimate and 10 metre wide tree belts for the upper estimate.

The results of this analysis indicate that income loss avoided by having mallee belts for shelter can range between $0.06 and $0.41 per green tonne of biomass when averaged over the amount of biomass produced per year in the 50 year life of the trees and depending on a range of assumptions about the factors listed above.

9.6.5 Biodiversity, protection of natural resources and Infrastructure

The value of improvements to salinity, biodiversity and aesthetics are challenging to quantify and difficult to express in dollars. Two studies that have made substantial attempts to quantify these benefits are Sparks et al. (2006) and Worley Parsons (2009).

Sparks et al. (2006) proposed a conceptual framework for managing the Western Australian natural resources, especially those at risk from salinity. They demonstrated the need for a systematic and outcome-focused procedure for selecting salinity investments by government agencies. Their report highlighted the feasibility of achieving salinity management goals for protection of biodiversity assets. They estimated the total cost of direct intervention across 48 natural resource assets to be $950 million over 30 years.

The plant-based proportion of the cost of protection of 30 biodiversity and waterscape assets (such as Toolibin Lake, which contains threatened species, communities and landscapes) was estimated to be $427 million including transaction costs. The analysis by Sparks et al. (2006) assumed planting of 125,000 hectares of trees. The trees' share of the cost of protection biodiversity and waterscape assets was estimated at $157 million.

They suggested that since public expenditure of this magnitude seems unlikely to occur in Western Australia, it is important that there is further investment in industry development to address the salinity threats while at the same time yielding economic returns. They argued that only by this strategy will the State be able to extend the range of assets adequately protected beyond a short list of the most significant. For the majority of threatened assets that will not be protected by public funding for on-ground works, the recommended strategy was to ensure that profitable systems of salinity management were available so that commercial decisions at the farm scale can also generate benefits at the catchment scale. 'Industry development' is the process of developing ways to treat salinity that are more cost effective and can be adopted in the course of a typical farm business. Strategic development of a commercially viable mallee biomass production industry could make a significant contribution in achieving this objective. The study reported in this chapter showed that if mallee belt plantings were to have the beneficial impacts discussed by Sparks et al. (2006), the benefits could amount to around $2.80 per green tonne of biomass over a 50 year period. This value, based on 10 metre wide tree belts, is the upper estimate reported in Table 9-3. The lower estimate in that table is based on 6 metre wide belts and the impacts assessed by a study conducted for an electricity generator in Western Australia (Worley Parsons, 2009).

Worley Parsons (2009) conducted a study that estimated the positive externalities of a regional biomass production system, as feedstock for bioenergy, based on plantings of 62,000 hectares of mallee belts in the south west of Western Australia. They analysed the regional scale benefits that may be expected to accrue from mallee growing operations common to each of the bioenergy options that were being considered by Verve Energy, an electricity producer in Western Australia. Benefits included the potential reduction of salinity costs accruing to agricultural producers, the reduction of salinity costs to households and businesses and the reduction of salinity costs incurred by local and state governments. Their model also incorporated calculations for social amenity and landscape aesthetics, biodiversity protection and waterway health.

The Worley Parsons (2009) study made explicit estimates of the value of the externalities that would be expected from the establishment of mallee biomass plantings in the Narrogin municipality. Their model accounted for the effects and costs of salinity with and without the mallee tree belts. They estimated benefits equal to the value of $17 million for mallee plantings, expressed in cost savings from reduced damage from salinity. For the purposes of this chapter the benefit can be expressed as $273 per hectare of mallee belts or around $0.82 per tonne of green mallee biomass averaged over the 50 year life of the project. The difference between the Worley Parsons (2009) finding and that of Sparks et al. (2006) highlights the sensitivity of results to assumptions about parameters for which empirical evidence is scarce and field measurements are difficult to obtain. However, these two studies indicate the likely range of positive externalities associated with establishment of a mallee biomass industry.

A quote from Garnaut (2011) is appropriate here: “adopting a carbon price will correct the negative externality associated with greenhouse gas emissions, including those from the land sector. However, while providing an incentive for biosequestration, a carbon price may or may not lead to improvements in biodiversity or other ecosystem services. Additional incentives need to be developed specifically to encourage the conservation of biodiversity and ecosystem services. This is separate from climate change mitigation policy, but the interaction of incentives to reduce greenhouse gas emissions (the carbon price) and incentives for biodiversity may enhance both the carbon sequestration and the biodiversity effects. Positive incentive mechanisms include grants, revolving funds, voluntary covenanting, tax concessions, offsets and auctions. The achievement of complementarity and consistency between carbon and ecosystem services programmes will require collaboration between the Australian, State and Territory Governments. Governments are currently working on a method to assess co-benefits of mitigation activities, which could be adopted for use in voluntary public reporting of co-benefits from offset projects under the CFI. Over time, just as carbon accounts are needed for carbon markets, further development of ecosystem services markets will require more comprehensive systems of environmental accounts that can deal with the complexity of natural systems. Valuable work on methods for valuing ecosystem services, including through payments for biodiversity benefits, is progressing in Australia and internationally”.

9.7 Conclusions

This chapter makes an assessment of the prospects for belts of mallee trees to develop into a viable, multi-purpose woody biomass crop for dryland agriculture in southern Australia. It provides detailed cost estimates, from planting and production to delivery of mallee biomass. The methodology presented here cohesively integrates the various bio-economic factors of production. The type of information that can be generated from analyses using this methodology can guide research and investment in mallee industry development.

The analysis reported in this chapter covered revenues from the sale of biomass and potential revenues associated with carbon credits, as well as monetised values for some co-benefits, all in the same units (current dollar value per green tonne of biomass produced). It showed that within the price range of $53 to $70 per green tonne, the full costs of production, harvest and delivery of mallee biomass are likely to be met.

The chapter discusses some of the co-benefits of mallee belts, of which mitigation of water-logging and recharge to groundwater are is the most significant on-farm benefits. Where such benefits occur, recognition of their value by the grower may facilitate the planting of mallee belts for commercial biomass supply. The value of benefits external to the farm that may motivate public investment in mallee development were also estimated. Reduction in rate of salinisation of public assets, including biodiversity assets, was valued at up to $2.80 per green tonne of biomass. The value of the on-farm benefits of shelter, erosion control and livestock protection were small in relation to cost of biomass. Analysis of benefits from diversification of farm business options and stimulation of regional economic development were not in the scope of this study. Benefits from the Carbon Farming Initiative are likely to be modest, with CFI revenues of only around $2.20 per green tonne of mallee biomass. Analysis of alternative schemes for pricing of greenhouse gas reductions was also not in scope of the study.

Valuations were presented within a range to indicate response to variation in design of production and supply chain systems, likely technological advances and variation in site productivity. For example, yield improvement through better site selection or water harvest will have a value of $3 per green tonne for every 10 percent increase in yield.

Significant gains can be made in scale, efficiency and profitability of industries based on farm grown woody biomass by further improvements in the design and productivity of mallee production systems; better understanding of their complementary role in dryland agriculture; cost reduction in the farm-to-processor supply chain; and advances in bioenergy technologies . Further impetus for the expansion and resilience of this emerging industry could be provided by government policies that better recognise that industries based on broad scale revegetation with woody perennials will reduce air pollution, increase national fuel supply security, improve natural resource management (e.g. dryland salinity), enhance the conservation of biological diversity, and reduce damage to public infrastructure (such as roads, water supplies and bridges).

9.8 **References**

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10. Supply and delivery of pongamia

10.1 Summary

The tree known as "pongamia" (*Millettia pinnata*) is of interest to the biofuels industry because it produces seeds that are rich in oil, and this oil may be processed to make biodiesel. However pongamia has little history of domestication and this presents multiple challenges for commercialisation. Possible commercial production systems were therefore studied. An economic analysis for a co-located plantation and oil extraction plant was undertaken to assess the financial viability of the pongamia enterprise in sub-tropical Australia and identify some of its key performance parameters.

Capital budgeting and cash flow analysis was conducted for a sample location in Queensland (Rosedale, Lat: 24.63° S, Lon: 151.92° E). The model was used to assess the performance and viability of the plantation under plausible management systems informed by the present knowledge of pongamia experts.

For annual seed yields ranging from 20 to 80 kilograms (in shell) per tree, the delivered cost of pongamia oil was estimated to be between \$2.22 and \$0.64 per litre. The seed yield range of 20 to 80 kilogram per tree is roughly equivalent to between 7 and 29 tonnes per hectare at a planting density of 357 trees per hectare. Major components of the delivered cost of oil are the capital expenses of land acquisition, plantation establishment and crushing plant construction. The major operational costs include mechanical harvesting; fertiliser and weed control, pests and diseases; seed crushing and freight of raw oil to a plant for further processing to biodiesel.

The costs with the greatest volume sensitivity are the capital expenses, overheads (consisting mostly of salaries and wages of employees), and harvesting, and crushing expenses. The cost per litre of oil for these items could be significantly reduced if seed yield could be increased.

Several scenarios were tested to demonstrate the effect of seed yield and oil price on the profitability and cash flow of the pongamia enterprise. In one scenario, a pre-tax return on investment of 11% could be expected if a median seed yield of 40 kilogram per tree (14 tonnes per hectare) could be achieved, although this is subject to the price of the oil rising gradually from \$1.34 to \$3.55 per litre over the next few decades. At lower prices or lower yields the plantation is not financially viable under the capital and operating costs used in this study.

Further research and development is more likely to be beneficial if directed to understanding and improving the seed yield of pongamia rather than to improvement in cost structures and marketing of oil. It is unlikely that substantial reductions can be made to the capital and operating costs assumed in this analysis. On the demand side, there is some agreement among market analysts that price of oil may rise steadily up to \$3.50 per litre in the next few decades. Since pongamia producers can expect to be price takers in the oil market, it is unlikely that oil prices will rise to a level where pongamia production can be financially viable at low yields.

10.2 Introduction

The use of biodiesel as a transport fuel in Australia is limited by the availability of feedstocks at a low enough price. Current production is primarily based on used cooking oil and tallow. However these feedstocks while available at low cost are only available in limited quantities as wastes or industry by-products, and the expansion of the biodiesel industry requires additional feedstocks at a low enough cost.

The pongamia (*Millettia pinnata*) is a leguminous tree that is found through much of Asia, northern Australia and the Pacific Islands. It is a species of the pea family and grows small pods (see Figure 10-1 below) that are rich in triglyceride oils that may be converted into biodiesel. The tree is not currently grown commercially in Australia. However, there is considerable interest in its seeds to produce oil, provided the cost is low enough.

Source: Stephen Schuck

Figure 10-1 Pongamia seed pods

The study reported here is of an economic analysis of a hypothetical commercial plantation of pongamia in Australia established to produce oil for use as feedstock for biodiesel (Murphy et al 2012, Jensen et al 2012, Odeh et al 2011). A model was developed to assess key performance parameters for a plantation and a co-located oil extraction plant (oil seed press). The aim was to investigate the financial viability of this oil-producing tree crop in sub-tropical Australia.

This model has capital budgeting and cash flow analysis capability. It incorporates a growth model of the tree as well as its seed and oil yield, integrated into a whole plantation system. The model provides a framework for evaluating the effect of tree yield and oil price on the profitability of the plantation. Both biological and financial aspects of production feature in the model so that the plantation is adequately described and simulations are meaningful.

Some of the variables of interest include growth of the tree in response to climate at a specified planting density, seed yield of the tree, oil content of the seeds, the price of oil and its future trajectory over the life of the plantation (40 years in this case), watering and harvest intervals, the cost of acquisition of land and other capital (e.g. plant and machinery) and the schedule of their replacement. An important feature of this model is that growth and yield of the tree are affected by seasonal rainfall observed for the modelled site.

The results of scenarios and sensitivity analyses presented here are a sample of possible outcomes of the model. Prospective investors may benefit from the use of this model when conducting feasibility assessment for commercial plantations. The use of this model can enable evaluation of alternative scenarios and analysis of its sensitivity to key assumptions. Results from such evaluations can help guide selection of priorities for future pongamia research.

10.3 Production and trade of biodiesel feedstock

Biodiesel production in Australia was at 21 million litres in 2005. By 2009 there were three major biodiesel plants in operation in Australia, which together with a few small producers had increased that production to 180 million litres per year (Geoscience Australia and ABARE 2010, ABARE 2010, Odeh et al 2012).

Biodiesel production in Australia is constrained by the limited availability of low cost feedstock (Farine et al 2012, Odeh et al 2012). Australia consumed 19 gigalitres (GL) of diesel fuel in 2010, and it is expected that diesel use will grow to 31 GL by 2030 (L.E.K 2011). Graham et al (2011) showed that the value of Australian petroleum net imports in 2009-10 was A$14 billion. Australia only produced 59 per cent of the petroleum products it consumed between 2009 and 2010. Australia's self sufficiency in petroleum production is expected to decline to 24 per cent by 2030. By 2030 net imports of oil could cost Australia almost A$70 billion per year in real terms if oil production declines and oil prices increase as expected.

Biodiesel markets are very closely linked to vegetable oil and oilseed markets. The three largest commodities in global vegetable oil production are palm, soybean, and rapeseed oil. In the EU the main biodiesel feedstock is rapeseed oil and in the US it is soybean oil. In these two large markets, the production and use of biodiesel has been incentivised by various institutional arrangements such as subsidies, import tariffs, levies and taxes. In Australia biodiesel is effectively excise free compared with petroleum derived diesel which has an excise of $0.38 per litre.

In a study by Apostolakou et al. (2009) the unit production cost of biodiesel from a plant with a capacity of 50,000 tonnes per year was estimated to be US$1.15 per litre (in 2008). The cost of feedstock includes the cost of raw materials including plant seed oil, methanol and catalysts. The delivered cost of rapeseed oil used for the production of fuel in that study was estimated at US$1.12 per litre of diesel. The cost of production of biodiesel from rapeseed in Spain estimated by Gomez et al (2011) was between $2.00 and $2.30 per litre in current Australian dollars.

A wide range of studies[1] indicate that the most important cost in the production of biodiesel is the cost of feedstock (75% -90%).

10.4 Biofuel potential for pongamia

In Australia, the interest in finding a biofuel feedstock from perennial crops has turned the attention of researchers and prospective investors alike to pongamia. This is because it is an oilseed plant that may be grown in a plantation setting as a tree crop established on land that is typically under pasture for livestock grazing in tropical and semi-tropical regions.

Murphy et al (2012) reviewed the opportunities for pongamia in Australia. Their review provided a snapshot of what is already known and the risks, uncertainties and challenges, based on published research and expert knowledge. It concluded that there are major knowledge gaps regarding growth and yield of pongamia in Australia. One of the priority research areas identified by Murphy et al (2012) was the application of economic modelling and analysis to the commercial viability of pongamia plantations.

Attempts to estimate the production potential of pongamia have found insufficient published or reliable information relevant to Australia. Little is known about its genetics, optimal growing environment, seed set, oil yield and the relationship between them. Even less is known about the financial returns that can be expected from investment in establishing a plantation and a seed crushing plant.

In the last few years peer reviewed publications about pongamia have in the main emanated from India. Only a few of them originated from research conducted in Australia. The Indian experience is commonly based on individual trees rather than on commercial plantations thus making it difficult to translate overseas experience to the biophysical conditions of Australia (e.g. Kesari & Rangan 2010). Murphy et al (2012) concluded that there are significant risks with the establishment of a pongamia industry in Australia, but with reasonable prospects for reducing these risks through a comprehensive research program.

The only known published economic analysis of pongamia in Australia was conducted by Odeh et al (2011). They used spatial analysis techniques to identify marginal agricultural regions suitable for growing pongamia. They defined marginal agricultural land as areas where profitable (agricultural)

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[1] Barnal and Sharma (2005), Pelkmans & Papageorgiou (2005), You et al (2008), Gui et al (2008), Gomez et al (2011), L.E.K (2011), Skarlis et al (2012), Kurika (2008) and Worldwatch Institute (2008)

production is limited by physical site conditions such as soil productivity, water availability as well as agricultural policy, macroeconomic and legal requirements.

Odeh et al (2011) estimated that under current and projected climate conditions 16 to 24 million hectares in mainland Australia could potentially meet minimal conditions for pongamia production. The suitable areas were mostly located in central north Queensland extending to north of Tennant Creek in Northern Territory in northern Australia and areas around Port Hedland in northwest Western Australia.

Odeh et al (2011) considered that pongamia plantations may be viable in northern tropical regions of Australia, with an estimated NPV for the case-study plantation of US$1,470 per hectare and a break-even period of 21 years. However it has not been possible to accurately compare their work with the work carried out for this report:

- It is not clear if their analysis included the cost of land and harvester.
- A number of production parameters were not specified, including the planting density, annual seed yield of trees, the size of the plantation, , and whether seed crushing and oil extrusion was included in the analysis.
- It is not clear what kind of harvesting system is assumed and how the analysis considered the annual costs of labour, fertiliser and mulch. Estimates for annual operating costs of a commercial plantation in this report are considerably larger than those presented by Odeh et al (2011).

The principal challenge for pongamia in Australia is the uncertainty of producing the oil at a competitive cost. This is mainly due to incomplete knowledge about the physiology of the tree and its growth and yield under different edaphic and agroclimatic situations. Kazakoff et al (2011) concluded that pongamia, with little or no history of domestication, presents many challenges for commercialisation. Before pongamia can be considered a reliable and significant source of feedstock for the biodiesel industry, further research will be needed to resolve the uncertainties about the seed and oil yield in the Australian context (Biswas et al 2011).

10.5 The pongamia tree

Pongamia trees have a mature height of 10 to 15 metres. Pongamia trees prefer humid tropical and subtropical climates (Kazakoff et al 2011, Csurhes & Hankamer 2010, Murphy et al 2012). Pod production starts around 4 to 7 years of age with full production from about 10 years onwards. Oil of pongamia seeds is of interest for biofuel production because of its desirable attributes for the manufacture of biodiesel (Biswas et al 2011, Jensen et al 2012).

Pongamia performs best in deep, well-drained, sandy loams with adequate moisture but it tolerates a range of soils (Csurhes & Hankamer 2010). Field trials have been conducted to measure growth of pongamia in south-east Queensland, Western Australia and the Northern Territory, but with only a few of the trials collecting quantitative data on growth and seed yield. Murphy et al (2012) reported preliminary observations from a few plantations in southern Queensland (Gatton in Brisbane, Yandina, Eudlo and Caboolture on the Sunshine Coast and Hinterland, and Roma in south-central Queensland) and from a plantation at Kununurra in the east Kimberley area in northern Western Australia.

Pongamia can grow in rainfed conditions with mean annual rainfall between 500–2500 mm and temperatures of 0–16 °C minimum and 27–50 °C maximum (Csurhes & Hankamer 2010, Murphy et al 2012). Mature trees can cope with light frosts, but require a dry period of 2–6 months.

In a plantation on the Sunshine Coast hinterland of Queensland, with an average rainfall of close to 1000 millimetres per year, trees were successfully established without irrigation and survived the drought period of 2007-2008. In this plantation pongamia production occurs in conjunction with a livestock enterprise, with sheep grazing the pasture growing between and under the trees (George Muirhead pers. comm.). Although the relationship between water and growth of pongamia is not yet well understood, experts consulted by Murphy et al (2012) recommended some irrigation or watering of trees during the establishment phase of the plantings.

10.6 Methodology for biophysical modelling

Due to the dearth of information on the growth of pongamia trees in Australia, a biomass production model was developed in this study from the well established principles of growth modelling for trees as described in Pretzsch (2010), Venn et al (2000), Fekedulegn et al (1999) and Vanclay (1995). The aim in the study was to build a production economics model that integrates a tree growth and yield model with the economic and financial aspects of the plantation. The biomass growth model of a representative tree within a commercial plantation setting was calibrated with the assistance of subject experts (George Muirhead, Julie Plummer, Gary Seaton and Peter Wylie pers. comm.).

A review of tree growth modelling by Vanclay (1995) highlighted the value of empirical evidence derived from carefully designed field experiments. Where an exploratory study is being conducted of a poorly understood tree crop, any functions based on biological data can provide a very useful input to bioeconomic modelling and financial analysis.

To understand the economically important parameters of a production system, it is possible to use preliminary growth and yield models from data available for a planting site, combined with subject expert knowledge and supplemented with data from other regions and countries. If a decision needs to be made now, some estimate of growth and yield is likely to be better than none (Venn et al. 2000, Battaglia & Sands 1998, Vanclay 1995).

Once a growth model is built to link into the production economics model, more accurate calibration can be undertaken as more accurate data becomes available from measurements on well designed sample plots, preferably in commercially managed orchards, or stands set up to simulate commercial operations. Ideally, measurements will span a sufficient period to average anomalous weather patterns and ensure that growth is not obscured by measurement error. Limited but reliable data covering the extremes are more useful than copious data clustered about the mean (Vanclay 1995).

When modelling the growth of a tree, an asymptotic growth function is preferred because a mature stand of trees achieves a relatively stable maximum of above ground biomass. The purpose in this study was to model geometric features of the development of a pongamia tree that are logically expected for its growth. This approach to modelling the growth pattern of a tree or a stand ensures that key growth features are incorporated in the model on logical grounds based on past experience and field observation of the tree or a close analogue tree crop in similar circumstances.

10.6.1 Biomass growth function

To be useful, theoretical equations must have an underlying hypothesis of cause or explanation. The growth of a tree can be represented as the difference between the synthesis and degradation of its building materials. Such synthesis and degradation could be expressed as an allometric function of weight and growth that over time produces a sigmoidal pattern with inflection points in the growth curve. This asymmetric biomass growth pattern has been shown to be empirically valid for many tree species within even-aged commercial stands of trees (Pretzsch 2010, Venn et al 2000, Vanclay 1995, Zeide 1993, Pienaar & Turnbull 1973).

The slope and the asymptote in the growth pattern are strongly influenced by site conditions such as soil pH, texture, depth and initial moisture, as well as climatic (particularly rainfall in non-irrigated systems) and agronomic or silvicultural management of the tree stand (John McGrath, Daniel Mendham and John Bartle pers. comm.) The growth function used in this study produces a pattern that is relatively slow both at the start of the life of the tree and at its maturity. Growth is faster in the middle stages of the growth and development of the tree. Thus the approach to the asymptotes is asymmetric in that the ending or final asymptote of the function is reached more gradually than initial or lower valued asymptote. The resulting sigmoidal curve, known as the Gompertz growth curve, has been found to be a suitable representation of the growth of trees (Pretzsch 2010, Fekedulegn et al. 1999, Venn et al 2000, Wong et al 2000, Gompertz 1825, Laird 1964).

$$W(t) = K \exp(\log((W(0))/K)\exp(-;t))$$

Where:

- *W* is the weight of the above ground biomass of pongamia at each stage of growth (age) of the tree.
- *t* is time in annual or yearly steps in the growth of the tree (age) spanning over 40 years.
- *W(0)* is the tree sapling size at planting;
- *K* is the maximum weight of a pongamia tree in a rainfed plantation (i.e. not irrigated) planted at the specified planting density. In other words, K is the maximum size that the tree can reach at maturity under the specified agroclimatic and edaphic conditions, and in the presence of competition from other pongamia trees, weeds and understory pasture being grazed by sheep. It is also contingent on the particular nutritional and other agronomic management regimes imposed on it.
- A is a constant that determines the growth rate of the tree. Its value is set at the value that will result in the maximum above ground biomass weight (K value) by a particular age observed for a pongamia tree.
- log() refers to the natural log.

The growth of the tree, described by the function described here, is first estimated for median annual rainfall of the site and then adjusted in response to the variation in annual rainfall from one year to the next. This produces a cumulative growth curve with a pattern as shown in Figure 10-2. This is the time series growth data used as a basis for estimation of seed yield of the plantation.

For the model used in this study, parameter set values for *W(0), K* and α were sourced from subject experts. This was complemented by the use of data for growth of other plantation or orchard tree crops, including macadamia, almond and olive (Stephenson et al 2003, O'Hare et al 2004, Quinlan & Wilk 2005, Hill et al 1987, Bustan et al 2011).

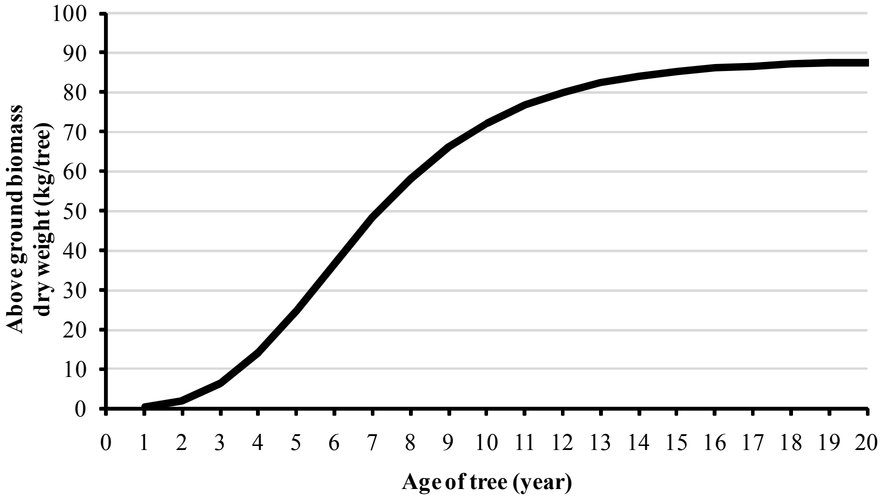


Figure 10-2 Pattern of growth of above ground biomass of pongamia in a commercial rain-fed plantation

10.6.2 Seed yield

There is wide variation in seed yield from pongamia trees assessed in Australia and also in overseas locations such as India. This includes absolute yield per tree and consistency of yield across seasons. A review by Graham et al (2011) of alternative feedstocks for biofuels, including pongamia, found a range of oil yields of between 2.50 and 8.03 tonnes per hectare per year. They found that in Australia suitable areas and likely oil yields are poorly known because there have only been a few small trials. The interaction between pongamia genotypes and the environment, including the effect of environmental stress on the oil yield is not well understood.

In Australia, pongamia seed production on irrigated plots in Western Australia ranged from zero to 30 kilogram per tree per year. In contrast, a 15 year old tree on a street in Brisbane was estimated to yield 80 kilogram of seed per year (Murphy et al 2012). Scott et al. (2008) report a potential yield in Australia of approximately 20,000 seeds from 10 year old trees per year. Based on their estimate of 1.8 g/seed this converts to a seed yield of 36 kg/tree or 12.6 tonnes of seed per hectare based on a planting density of 350 trees per hectare, provided all trees were productive.

Studies in India have reported seed yields in the range of 9-90 kilogram per tree per year (Dwivedi et al 2011). In one instance an unusually high yield estimate of 250 kg per tree has been reported (Kesari & Rangan 2010). Yield estimates from India are often sourced from individual trees rather than being based on the average of a plantation over several seasons (Kazakoff et al 2011, Murphy et al 2012). It is worth noting that seed yield of commercial orchards of macadamia and almonds tend to range between 5 to 20 kilograms of nuts in shells per tree per year, equivalent to about 1 to 6 tonnes per hectare at 200 to 320 trees per hectare (Stephenson et al 2003, O’Hare et al 2004, Wilkie et al 2010, Hill et al 1987). The lower yield estimates are for non-irrigated plantations.

In this report the seed yield of a pongamia tree is expressed as a function of above ground biomass and the rainfall of each season. This produces a seed yield function that incorporates a degree of seasonal variability that is likely to exist in a rain-fed production system. One of the yield scenarios used in this study is 20 kilogram of seed per tree per year for mature plants at a planting density of 357 trees per hectare, which is around 7 tonnes per hectare per year for a mature plantation. This was the expected yield of Murphy et al (2012) and it concurs with yield estimates of Scott et al (2008) and Graham et al (2011).

Higher seed yields were also analysed to test the sensitivity of the results to yield variations. The median and average yields in the production model of the plantation are slightly lower than those depicted in Table 10-1 because for the first four years of the plantation trees are not in production and yields are assumed to be negligible. For instance, in the 20 kilogram per tree yield scenario, the average plantation seed yield is 17.3 kilogram per tree and the median yield is 17.8 kilogram per tree per year.

In this study the modelled relationship between seed yield and rainfall was assumed be:

$$\textbf{\textit{Yield = 0.02 * Rainfall}}$$

Where yield is expressed in kilograms of seed (including shell) and rainfall is the annual rainfall in the range of 800 to 1200 millimetres. In years with annual rainfall outside this range, seed yield is constrained to the minimum and maximum yields expressed by the yield equation described above, as indicated by data in Table 10-1. This yield response function to rainfall was calibrated based on data obtained from consultations with subject experts (Julie Plummer and George Muirhead pers. comm.).

Table 10-1 The relationship assumed between rainfall and seed yield of pongamia in each of the yield scenarios for a plantation with planting density of 357 trees per hectare

Summary statistics	Annual rainfall	Tree yield as seed in shell (kg/tree/year)		
	(mm)	20	40	80
Min	555	17	35	69
Max	2220	26	52	104
Median	922	20	40	80
Mean	1031	21	42	85
Std Dev	349	4	7	14

10.6.3 Oil content

Oil content of seeds from pongamia trees growing in Queensland ranged from 35% to 43% with similar results reported for seeds from a trial plantation in the north of Western Australia with oil content ranging from 31 to 45% (Kazakoff et al 2011 and Biswas et al 2011). Similar oil content has been reported in India (Mukta and Sreevalli 2010). About two thirds (by weight) of the seed is the meal or cake which remains after oil has been extracted from the seed. Although the meal contains about 30% protein it cannot be used as animal feed because it contains chemicals that make the meal unpalatable to livestock. It also contains anti-nutritional factors that affect the digestibility of protein and carbohydrates in herbivores (Murphy et al 2012).

The best use of the meal appears to be as mulch, especially if it is produced from a seed crushing plant that is collocated with the plantation since it minimises transport cost. The same applies to pod shells and prunings. In future, and depending on the price of fuel and fertilisers, this organic material may be combusted to produce electricity (Murphy et al, 2012).

In this study the shells are assumed to constitute 50% of the weight of seeds in shells (pods). Oil content of the seed is assumed to be 40%. Figure 10-3 shows how the annual yield of oil, meal and shells is influenced by rainfall from one season to the next in the base case scenario. The magnitude of annual variation in oil yields is based on a response function that is influenced by age and the rainfall of the season.

Annual seed yield of the rainfed pongamia is shown in Figure 10-3. The variability of seed and oil yield is a function of the variable rainfall from one season to the next. Since seed yield depends on growth of the tree, the first harvest in year 4 produces less than 5 kilograms of seed per tree from immature trees. This means that at first harvest only around 1.5 tonnes seed in shell is harvested, resulting in production of 314 litres of oil per hectare and a total volume of 157,000 litres of oil for the whole plantation of 500 hectare.

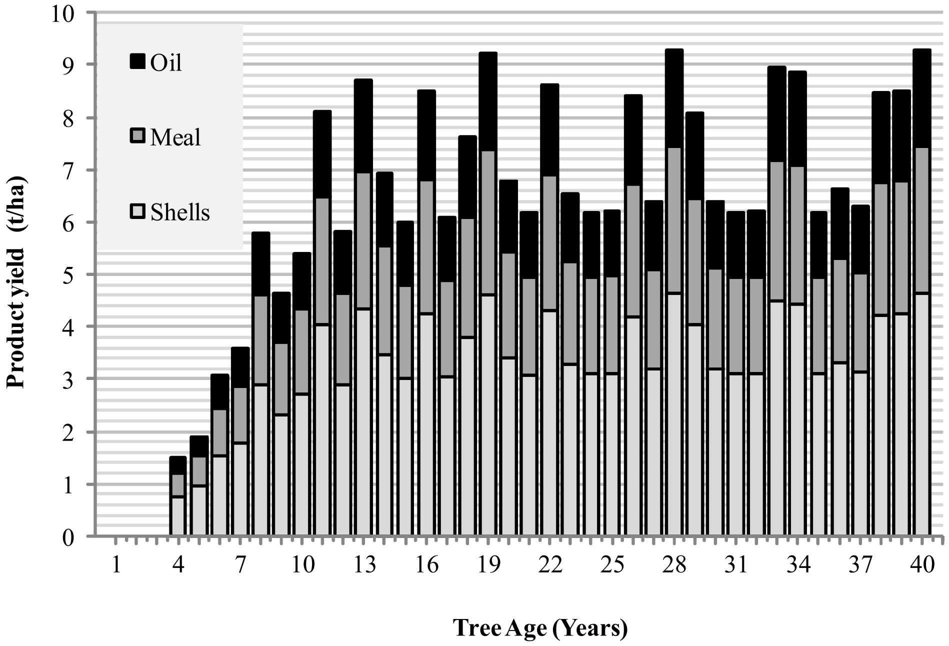
When the trees are mature, after year 10, annual production is between 10 and 26 kilograms of seed per tree depending on the rainfall. The average annual production of seed in shell is 3,345 tonne for the entire plantation, which is close to 6.7 tonnes of per hectare. The standard deviation for production of seed in shell is 978 tonnes per year.

The average annual volume of extruded oil is about 630,000 litres for the whole plantation (around 1260 litres per hectare) with a seasonal variability indicated by the standard deviation of 204,000 litres and attributable to variation in rainfall in the region. It must be emphasised that the yield estimates and the seasonal fluctuations reported are based on a mathematical model rather than direct observations from commercial trials. A significant body of research work is required to provide firm estimates of the yields that may realistically be expected from pongamia.

In India, pongamia grows in areas with an annual rainfall range of 500 to 2500 mm, shedding its leaves in April and forming new leaves from May onwards. Flowering is annual and it occurs about 4 to 5 years after planting. Flowers appear from April to June with pods ripening from February to May of the following year (Dwivedi et al 2011, Sangwan et al 2010). Pollination occurs by insects and the presence of bees substantially improves seed set and yield (Julie Plummer and Ni Luh Arpiwi pers. comm.).

Australian experiments have found that seed yield of pongamia is severely affected by heavy rain periods during the time of flowering. Flowers collapse due to heavy rain and fruit does not form due to absence of insect pollination. In Australia, pongamia appears to be deciduous during cold periods. It displays dormancy in winter and in drought. Minimum temperatures above 15 degrees appear to be required for at least six months before foliage is produced. The effect of extreme droughts, frost, floods, cyclones or extreme heat on pongamia’s seed production and oil yield is not well understood (Murphy et al 2012).

Often seed pods remain attached to the tree at the time of flowering for the following season. This may adversely affect yields as mechanical harvesting may damage the flowers. (Murphy et al 2012) called for investigation of the use of abscission chemicals for release of mature pods prior to flower development.



Sources of seed yield variability are influenced by variable rainfall for a plantation with a planting density of 357 trees per hectare and median yield of 20 kilogram per tree.

Figure 10-3 Annual yield (in tonnes per hectare) of oil, meal and shells from rain fed pongamia trees

Pongamia is an obligate, out-crossing species, giving it a high degree of variability between trees in their phenology, growth and reproduction. This lack of uniformity in timing and quantity of seed production is a major impediment to commercial operations (Murphy et al 2012). High inter-tree variability must be managed with a genetic selection and improvement program along with clonal propagation for commercially successful plantations to be established.

Clonal propagation of elite trees is necessary for uniformity in plantations allowing equal usage of row space, avoidance of shading and competition, uniform flowering period, management and harvesting regimes and predictable quality of products (Kazakoff et al 2011). Pongamia experts consulted by Murphy et al (2012) concluded that while propagation from elite stock is often promoted, there is very little information on how these elite trees are to be identified or selected. The criteria by which a genetic line of trees can be judged to be of “elite” type remains to be fully described (Biswas et al 2011).

Alternate fruit bearing (also known as biennial bearing) of fruit and nut trees challenges the industries dependent on them. Some researchers consider irregular fruiting as the normal behaviour of trees in their natural environment. It has been proposed that in a broad evolutionary sense alternate bearing should perhaps be understood as a phenomenon of homeostasis. Trees may respond to stress by shifting their resources to vegetative growth and structure for a year or two, to build the resources for subsequent fruiting. The modern management of fruit trees in orchards and plantations attempts to eliminate as many of the natural stresses as possible (e.g. drought and pests), thus encouraging more regular fruiting and creating a stable production system (Bustan et al 2011).

An industry based on rainfed pongamia plantations is likely to experience seasonal variability of yield, which will need to be included in analysis of production systems. Alternate bearing, if it is found to occur on a regular basis in all plantations, will have an additional negative impact on the viability of the plantations. This makes identification, selection and propagation of varieties that produce high yields on a regular basis a priority area of research in Australia. In the analysis reported here alternate bearing is assumed not to occur at the modelled site. However, the seed yield of the plantation is assumed to vary in response to annual rainfall.

10.6.4 Nutrition

Pongamia root nodules contain less nitrogen-fixing tissue than expected for a legume tree. It is not clear if this is caused by suboptimal bacterial inoculant, or if it is the inherent nature of the species (Kazakoff et al 2011). Murphy et al (2012) suggested that application of fertiliser is likely to contribute to establishment success and early growth. Addition of phosphate, potassium and selected micronutrients may be required over the long-term to maintain soil fertility. Soil and foliar analysis would be required to provide a basis for establishing appropriate fertiliser regimes.

In this study the nutritional requirements of the plantation were based on Sangwan et al (2010), Murphy et al (2012) and Wani et al (2006), whose work suggested that application of some nitrogen (N), phosphate (P) and potassium (K) would maintain the productive capacity of the plantation. Sangwan et al (2010) reported the amount of N, P, K and Calcium (Ca) in the leaf and fruit of pongamia grown in India, as shown in Table 10-2. At present there is no definitive recommendation for the type and the rate of fertilisers required. The assumptions used in this model were also influenced by the recommendation made by Quinlan and Wilk (2005) and O'Hare et al (2004) for macadamia crops in northern NSW and Queensland.

Table 10-2 Nutritional composition of leaf and fruit of pongamia in India as reported in Sangwan et al (2010)

Nutrient	Leaf (% of dry weight)	Seed and shell (% of dry weight)
Nitrogen (N)	1.16%	5.1%
Phosphate (P)	0.14%	0.61%
Calcium (Ca)	1.54%	0.65%
Potassium (K)	0.49%	1.3%

Fertiliser costs are assumed to ramp up in step with the growth and harvest of trees, starting at $30 per hectare in the first year when plants are small and increasing to nearly $300 per hectare when trees are mature and being harvested as shown in Table 10-3.

Table 10-3 Rates and cost of fertiliser applied to pongamia in this study (excludes mulch)

	Unit	Years since establishment of plantation					
		1	2	3	4	5	6+
Fertiliser amount	kg/ha	66	132	189	330	440	660
Nitrogen	kg/ha	0	0	0	0	0	0
Phosphate	kg/ha	3	6	9	15	20	30
Potassium	kg/ha	16	33	47	82	109	164
Sulphur	kg/ha	3	7	10	17	23	35
Calcium	kg/ha	7	13	19	33	44	66
Fertiliser cost	$/ha	30	59	85	149	198	297
Fertiliser cost	$/tree	0.1	0.2	0.2	0.4	0.6	0.8

Fertiliser is assumed to be CSBP Super Potash 1:1 contains: P 4.6%, K 24.8%, S 5.3%, Ca 10%. Cost of super potash 1:1 is $450 per tonne.

In this report the nutritional requirements of the crop are assumed to be met by a combination of nutrients from commercial fertilisers and from the mulch derived from by-products of the seed crushing plant. The seed meal and seed shells are assumed to be returned from the co-located crusher back to the property. Pruned branches and twigs clipped by the harvester are also assumed to be returned to the plantation to avoid loss of nutrients. It is assumed in this study that the plantation manager would choose a type and application rate of fertiliser that, combined with the mulch, would adequately replace the nutrients exported from the field.

10.6.5 Weeds, pests and diseases

Pongamia experts recommend that, for the first three years grazing livestock be excluded from the plantation in order to protect the trees from being damaged. This will necessitate mechanical control and removal of pasture from under and between the trees as well as some chemical control of weeds. After that period sheep can be introduced into the plantation to manage the grasses and weeds. This will in turn provide a secondary income from the plantation. In a mature plantation and under careful management of grazing, sheep tend to feed only on the more nutritious pasture plants and only browse on the lower branches of the trees if other feed is scarce. This minor ‘pruning’ carried out by stock is likely to be beneficial in controlling root or base sprouting (Murphy et al 2012).

Except for minor foliage damage, little evidence has been found in Australia for significant damage to pongamia by pests and diseases. Establishment of this tree as a crop may, however, provide increasing opportunity for pests and pathogens to establish and the consequences of this needs careful assessment (Murphy et al 2012).

In this analysis, an ongoing annual cost of $42 per hectare was assumed for weed control from first year after establishment. Pest and disease control was assumed to cost $10 per hectare in year one escalating to $197 per hectare by year 10 and beyond.

10.7 Methodology for economic analysis

10.7.1 Development budgets and cash flow

A model was developed to investigate the economic viability of the proposed pongamia oil production system. It includes a 500 hectare pongamia plantation and an oil extraction plant (seed press) co-located with the plantation. Annual seed production is determined by the biophysical model and then used in the economic model, which simulates the annual profitability and cash flow of the oil production system. Oil price is specified by the analyst for the life span of the plantation.

The sections that follow describe the main features of the plantation, with particular emphasis on the financial assumptions that were made in conducting this analysis. The design of the bio-economic and cashflow analysis model includes a number of development budgets to estimate the cash flow over a 40 year period.

In building this model, the components were assembled so that the model is:

- sufficiently general as to be applicable to more than one plantation, after careful site calibration
- modular, with growth prediction separate from management simulators
- able to simulate the effects of major management options such as the year of first harvest
- adjustable for scale so that a skilled analyst can modify the model to represent a smaller or larger production system
- using biologically derived functions for growth and yield and their response to rainfall
- driven by currently available data rather than waiting for new empirical data that would take years to deliver
- flexible with options to alter simulation of individual processes
- amenable to sensitivity testing by the analyst

- user-friendly, with flexible "plain English" tables for reporting inputs and outputs in order to enable realistic and effective interpretation of results and documentation of the model
- designed so that it can estimate the cash flow stream and profitability indicators for a range of alternative of scenarios.

10.7.2 Treatment of equity, debt, tax and depreciation

It is assumed that the owner of the pongamia enterprise has full equity and can fund the initial land acquisition and other capital costs; the annual operating costs from year to year and the expenses associated with the routine replacement of plant and equipment associated with the plantation and the oil extrusion plant. Thus the ability to repay borrowed funds is not considered in the analysis.

The expenditures and revenues of the business are calculated at the pre-tax level. Individual investors differ widely in their taxation arrangements and an analysis of such matters is beyond the scope of this study. Depreciation is allowed for by accounting for the useful life of plant and equipment, which ranges from 4 to 10 years. The capital budgeting modules include the scheduled replacement cost of plant and equipment.

10.7.3 Discount rate and inflation

There are two methods for discounting future cash flows in order that all expenses and revenues are shown as present value. One method requires the estimation of discounted future cash flows in nominal terms and the other in real terms. Both approaches applied consistently, will give the same net present value (Peirson et al 2002, Brennan 1998, Zhang & Pearse 2011).

The Australian economy does have some underlying and variable inflation in cost of inputs (e.g. wages) and in the price of outputs of the private and the public sector enterprises -typically 2-3% (RBA 2012, Peirson et al 2002). Inflation increases the general level of prices causing a fall in the purchasing power of money. One way of accounting for inflation in evaluation of long term investment projects is to leave the prices stated in current values while adjusting the interest rate used in project evaluation upward to allow for inflation. The nominal rate of interest that is commonly observed in financial markets is the sum of two components: the inflation rate and the real rate. The inflation rate, an allowance for inflation, is the rate at which a value must grow in current dollars to maintain its value: in constant dollars. The real rate of interest, the return on capital after allowing for inflation, is the difference between the nominal rate of interest and the inflation rate.

This approach is useful when the future rate of inflation is unknown in a particular sector, as is the case for biofuels and pongamia. The rate of price and cost change for different outputs and inputs over the investment period in these industries may differ from the rate of inflation in the general economy. Therefore, the pongamia oil production project was evaluated in constant dollars. In this case, all costs and benefits were estimated in 2012 dollars as the base year. Then, using an inflation-free real rate of interest of 7%, the stream of project's future benefits and costs were reduced to their present values.

The rate of interest (discount rate) is critically important in evaluating investments. The appropriate rate of interest is the investor's opportunity cost of capital. This is the rate that the investor can earn on capital invested elsewhere (at the margin). Real rates of return on private equity capital have been in the order of 6% to 7% in Australia and comparable nations. Private rates must be higher than the rates for long-term government securities because, unlike government projects, private incomes are taxed, and because private securities are riskier than government securities. The complexity of the relationship between real and nominal rates of return makes the approach used for this analysis easier to handle in practice (Brennan 1998, Peirson et al 2002, Zhang & Pearse 2011).

10.7.4 Profitability and return on investment indicators

The cumulative discounted net revenue is called Net Present Value (NPV). NPV is the lump sum value of the project expressed as the sum of discounted annual net returns accrued at each stage in the life of the plantation. The cumulative discounted net revenue in year 40 is the final NPV of the project.

The Internal rate of return (IRR) of the pongamia project is the rate of return that equates the present value of the plantation's cash flows with its initial cash outlay. IRR is similar to an interest rate that is earned from the return on the investment in the plantation during its life in addition to the recovery of the investment outlay. Put another way, IRR is the discount rate that causes the NPV of the cash flows of the pongamia plantations to be zero. It also represents the highest rate of interest an investor in the plantation could afford to pay for borrowed funds without losing money (Brennan 1998, Peirson et al 2002, Zhang & Pearse 2011).

10.7.5 Cash flow indicators

NPV and IRR indicate the ability of the project to be profitable and produce a return on investment. Investors and business managers also require an indication of the pattern of cash flow for a project. Investments that are profitable in the long run but have negative cash flow for prolonged periods may be rejected in favour of projects with earlier positive cash flow traded off against slightly lower long term profit margins.

Peak debt and payback periods are two useful indicators of the cash flow consequences of investing in a pongamia plantation. Peak debt is the highest discounted cumulative cash deficit in the life of the plantation. Payback period is the year when the discounted cumulative cash flow of the project becomes positive. The payback period is the time it takes for the initial cash outlays to be recovered from the project's net cash flows. It is calculated by summing the net cash flows from a project in successive years until the total is equal to the initial cash outlays.

Payback period is not a measure of a project's profitability. It is best used in conjunction with NPV and IRR and it helps provide an indication of how long funds are likely to be committed to a project (Peirson et al 2002).

Once a decision is made to finance and establish a pongamia plantation, it is the cash flows of individual years that will be the key managerial concern. In this regard, an important cash flow indicator is the year that the income from the sale of oil will begin to exceed the expenses incurred in operating the plantation and the seed crusher. This is the first positive cash flow year and is estimated using undiscounted revenues and expenses. Sometimes a project might produce a positive cash flow for one or two years before large machinery replacement costs create negative cash flow years for one or more years.

10.8 The plantation

10.8.1 Property location & land value

In this study it is assumed that the land for the plantation is purchased as part of a rural property situated near Rosedale (Lat: 24.63° S, Lon: 151.92° E) between Maryborough and Malborough in Queensland. The cost of the land is $2,000 per hectare and was based on a sample of properties offered for sale in the region as advertised by real estate agents in 2012. The plantation area is 500 hectares and there is an additional 10 hectares of land allocated to roads, yards, sheds, seedling nursery, storage facilities and the seed crushing and oil extrusion plant.

The hypothetical case study property is a grazing property with highway frontage and an access road. In its original state it is divided into several paddocks, with stock water and adequate fencing. The annual rainfall of the site is typically1031 mm, with a minimum of 555mm and a maximum of 2220 mm since 1971. The soil type of the property is deep red loams suitable for growth of pongamia. There are also sheep yards and livestock handling facilities and sheds. The property has a homestead with an office.

In this study the land allocated to the plantation is subdivided after purchase and fenced into 50 hectare blocks, or pongamia groves, to facilitate efficient management of trees and livestock in the plantations. This requires approximately 19 kilometres of fencing at $4,500 per kilometre. Total cost of fencing is $85,901.

The profitability of grazing properties in this region is similar to the industry benchmarks published in Aginsights (2011 & 2012) (George Muirhead pers. comm.). The average profitability from livestock grazing enterprises is $124 per hectare and the median profitability is $81 per hectare for properties managed with sheep or cattle. The standard deviation of livestock profitability is $129 per hectare due to inter-seasonal variability in rainfall and prices of wool and meat. These benchmark profitability estimates are expressed in 2012 dollars.

10.8.2 Planting density and spacing of trees

Planting density and spacing of trees is influenced by two main factors. The first is the impact of planting density on seed yield of a stand of trees in a rain-fed production system. The second is the requirement for access to the trees by a mechanical harvester and impact of planting design on the cost of harvesting.

Mechanical harvesting of pongamia has been demonstrated in Australia but harvesting methods for plantations require considerable further development and testing. The type and size of mechanical harvesters influence planting design and tree spacing. Umbrella shakers and gantry style harvesters require a minimum of 7 m spacing between rows. A pongamia trial plantation at Caboolture in Queensland has trees planted in 5 x 7 spacing. Tree spacing of 4 to 5 metres with 7 m spacing between rows resulting in approximately 320 trees per hectare is considered adequate for maximizing tree yield and providing spacing for mechanical harvesting (George Muirhead pers. comm.).

It is assumed that, once planted, trees are maintained for 40 years and not replaced with improved yield varieties. This may be a simplification that will require further analysis in the future..

10.8.3 Establishment costs and capital expense

The capital expenses associated with establishment of the plantation and the crushing plant are shown in Tables. Table 10-4 and Table 10-5. Table 10-4 includes the cost of acquisition of the land, fencing, seedlings, site preparation including weed control, planting and pegging of trees and the cost of fertiliser and mulch. These costs are lower than those experienced in establishing orchards for olive and almond industries, due mainly to the economies of scale associated with a 500 hectare plantation positioned on a larger rural property (Beckingham & O'Malley 2007, Verghese et al 2009).

Table 10-4 Establishment costs of the plantation shown in chronological order of the operations

Item ^	Value	Salvage value #
Land occupied by trees	$1,000,000	$1,000,000
Fencing	$85,901	$85,901
Tree seedlings	$714,000	0
Discing twice and ripping	$170,000	0
Marking out, site pegs and planting (with hired labour)	$328,023	0
Weed control, fertiliser & mulching (incl. labour & tractor)	$608,592	0
Total	$2,906,515	$1,085,901

*^ The life span of items is for the life of the plantation (40 years) * Includes fuel, oil, repairs and maintenance*

 # Salvage values are expressed in 2012 dollar value undiscounted

Salvage value is an estimate of the remaining value of an investment at the end of its useful life. For farm machinery (tractors and implements) the remaining value is a percentage of the new cost of the investment. The remaining value depends on the equipment type, years of life in service and the market for a well used machine. For other investments including buildings and miscellaneous equipment, the value at the end of its useful life is zero. The salvage value for land is the purchase price because land does not usually depreciate.

The purchase price and salvage value for plant and equipment of pongamia plantation and the attendant crushing plant are shown in Table 10-5. This table also shows the value of the harvester, sheds and the equipment associated with major cost items. Their productive life spans range from 4 to 10 years. In the cash flow model, these items are scheduled to be purchased again at the end of their lifespan, with the acquisition cost being the purchase cost of a new item less any salvage value of the old one.

Table 10-5 Capital expense associated with machinery and crushing plant and equipment

Item	New price	Purchase year ^	Life span (years)	Salvage value
Vehicles-Truck, Ute, Tractor	$182,000	@ estab	5	$26,000
Implements #	$112,000	@ estab	4 to 9	$4,500
Crushing plant and equipment	$715,611	3	10	$161,360
Machinery in shed	$20,000	@ estab	10	$0
Shed building	$114,770	@ estab	15	$0
Harvester	$900,000	3	10	$170,000
Harvesting bins and trailer	$28,000	3	10	$0

@ estab means the year of establishment of the plantation
 # Includes slasher, trailer, spray units, fertiliser spreader. Salvage values are 2012 dollar value undiscounted

The establishment cost estimated for a 20 hectare, non-irrigated macadamia plantation in Queensland in 2004 was estimated to be between $50 and $60 per tree, excluding the purchase costs of land and house (O’Hare et al 2004). . The economies of scale of the establishment of the pongamia plantation, modelled in this study, results in a much lower establishment cost of around $11 per tree or about $3,800 per hectare of trees. This cost excludes acquisition cost of land, tractor, harvester, oil extrusion plant and associated equipment and implements.

10.8.4 Harvest and on farm haulage

Harvesting is assumed to be carried out with a Colossus harvester (Ravetti & Robb 2010, http://www.leda.net.au, viewed 23/07/2012). This type of harvester and the associated equipment, which includes bins and trailers (excluding tractor), is valued at $928,000 purchased as new equipment (Henry Higgins of Leda and George Muirhead pers. comm.). Some pruning is required during the establishment phase (first 3 years) in order to encourage trees into a shape that lends itself to efficient harvesting. Pruning is also required after harvesting commences, to maintain trees at a height of around 6 metres. According to industry benchmarks reported by the Australian and New Zealand olive growers published in a newsletter in 2006, a single Colossus harvester is capable of harvesting a 500 hectare plantation. The average harvesting cost, for the yield scenario of 20 kilogram per tree, is around $0.06 per kilogram of seed in shell (Table 10-6). This includes the wages of drivers for the harvester and the on-farm haulage truck and associated equipment (Henry Higgins pers com at http://www.leda.net.au, viewed 23/07/2012) and concurs with the harvesting costs estimated by Ravetti and Robb (2010) for similar machinery used for continuous mechanical harvesting in modern Australian olive growing systems.

Table 10-6 Operating costs of the harvester

Cost item for harvesting	Value
Total annual harvest cost (including cost of two drivers)	$202,677
Operating cost per hectare per year	$405
Operating cost per tree per annual harvest	$1.1
Average cost kilogram of seeds in shell	$0.06

(for 20 kg/tree yield scenario)

10.8.5 Seed crushing and oil extrusion

The seed crushing plant is built in the third year and commissioned a year later to start processing the seeds of the first harvest. Key assumptions for the seed crushing plant are shown in Table 10-7. This plant processes an average of 3,345 tonnes of seed in shell (1,672 tonnes of hulled seed) each year under the yield scenario of 20 kg of seed per tree (7 tonnes per hectare). The first harvest has the lowest production at 752 tonnes of seed in shell. In years of favourable rainfall the plant's maximum production is needed, at over 4,600 tonnes of seed in shell. The plant will operate for 134 days per year for average seed production under the yield scenario of 20 kilogram per tree. However, in years with above average production the plantation is likely to operate for a greater part of the year. Given the seasonal variability and the lack of certainty in the production of the plantation, the assumptions about oil extrusion plant appear realistic. Since crushing is a significant cost in the production of oil there will a great deal of interest in reducing this cost by matching the demand on the plant to the variable supply of seeds. The possibility of storage of pongamia seed from one year to the next offers the potential to balance the load on the crusher in high production years. Labour, involving two employees, is the main cost item in the operation of the crushing plant. The plant operating cost is estimated at $0.27 per litre of extruded oil for an average production year. It is assumed that the labour for the crusher can be adjusted to match the volume of harvest for each season, reducing its overhead costs. Most pongamia producers should be able to switch the use of some of their labour from the plantation to the crushing operations.

Table 10-7 Operating costs for operation a seed crushing and oil extrusion plant

Parameters	Value
Operating hours per day	10
Effective daily crushing capacity of the plant (tonnes per day)	12.5
Labour days required per year for repair and maintenance	5
Labour hours per tonne of oilseed crushed	0.8
Percentage of oil recovered	95%
Seeds crushed (tonnes per year, average for hulled seeds)	1,673
Tonnes of meal produced per year	953
Litres of oil extruded per year (adjusted for density)	697,688
Number of days required for crushing in an average harvest	134
Annual cost of labour (two employees)	$221,000
Annual cost of power, repairs and maintenance	$38,650
Operating cost per litre of extruded oil	$0.27
Freight of oil to processor within 100 km ($/l)	$0.10

The cost of freight of oil to a refiner within a 100 km distance from the crusher is estimated at $0.10 per litre. This estimate is based on data published in RACQ (2011) with supplementary information obtained from AIP (2012b). It is assumed that Tank Containers (ISO Tanks) are used as short-term storage at the crusher and for the transportation of the extruded oil from the crushing plant to the refiner. Typically, each ISO tank has a 20,000 litre capacity and costs from $25,000 to 30,000 each (Direct Logistics Pty Ltd, 2012).

With average oil production of just over 5,000 litres per day the pongamia crushing plant will require three ISO tanks so as to allow for two tanks in circulation between the crusher and the refiner, while the third tank is being filled by the crusher. A delivery run is made when the crusher has filled an ISO tank and begins filling a second. The third empty ISO tank is at the refinery after being left there in the previous delivery run. The truck collects the empty tank from the refinery, delivers it to the crusher and returns to the refinery with the full tank to complete that delivery run. The capacity of the ISO tanks is sufficient to act as a three to four day surge buffer at the crusher, enabling continuous crushing to be coordinated with periodic transport. Tanks do not require cleaning between uses and loading and unloading times for the truck are minimised. If in practice the return trip time for delivery of the tank container can be reduced to 4 to 5 hours then the cost of delivery of oil may be reduced to $0.05 per litre, because the contractor’s truck would need to devote only half a day to delivering each tank of pongamia oil.

Cost of establishment and commissioning of a seed crushing and oil extrusion plant is estimated at close to $716,000 and consists of the items in Table 10-8. The capital cost and the annual operating expenses of the plant modelled here are close to those reported for seed crushing and oil extrusion plants associated with biodiesel manufacturing industries in Europe and Canada (Gomez et al 2011, Reaney et al 2006, Gary Seaton pers. comm.).

Table 10-8 Capital costs for a seed crushing and oil extrusion plant

Crusher capital cost items	Cost
Building & plant housing	$300,000
Storage bins for seed and meal	$170,111
Mechanical press (Rosedown)	$100,000
Oil tanks x 3 (ISO tanks)	$81,000
Power source for press	$20,000
Civil works & cost of connection for electric, water, etc.	$25,000
Seed dehuller & cleaner	$10,000
Filtration equipment, valves, pumps & plumbing	$9,500
Total plant and equipment	$715,611

10.8.6 Overheads and fixed costs

Overheads and fixed costs are annual expenses that remain constant in the short term regardless of the level of seed or oil production from the plantation. Overhead costs include shire rates, licenses, insurance, salary of manager and wages of other permanent labour, administration, electricity, gas, fuel, maintenance of business infrastructure (buildings, fences, office, communications and information technology) and maintenance expenses of passenger vehicles.

Once a plantation is established, and all the required machinery and equipment are purchased, the overheads remain relatively constant from one year to the next. With overhead costs predetermined in the short-term, management choices regarding production generally affect the variable costs incurred in production of seed and oil. Overhead costs of the pongamia oil production system are estimated at $273,000 per year as shown Table 10-9. These costs are similar to overheads for other rural properties in NSW and Queensland (Aginsight 2012, O’Hare et al 2004). When averaged over the life of the plantation, the unit cost for overheads is around $0.40 per litre of oil.

Table 10-9 Fixed costs for operation of a pongamia plantation and oil extrusion plant

Description of annual overhead expenses (fixed costs)	Cost
Permanent family labour (orchard owner operator) (incl. super, insurance)	$120,000
Permanent hired labour (includes superannuation + insurance)	$60,000
Administration (rates, insurance, rates, licences, superannuation)	$70,000
Electricity, gas, fuel and other minor expenses for operational purposes	$13,000
Repairs & maintenance of buildings, fences, office, IT and cars	$10,000
Total annual cost	$273,000

10.8.7 Annual operating costs

The annual operating costs of the pongamia business include the fixed costs described above. They also include variable costs, some of which change, according to the size of the harvest and the volume of oil produced. These costs increase in high yielding years and are generally lower in years with low production, as shown in Figure 10-4[2]. After plantation establishment, operating costs escalate rapidly for a decade before reaching an asymptote with a degree of annual variability. This variability reflects the impact of variable rainfall in seed production and thus on harvesting and crushing costs.

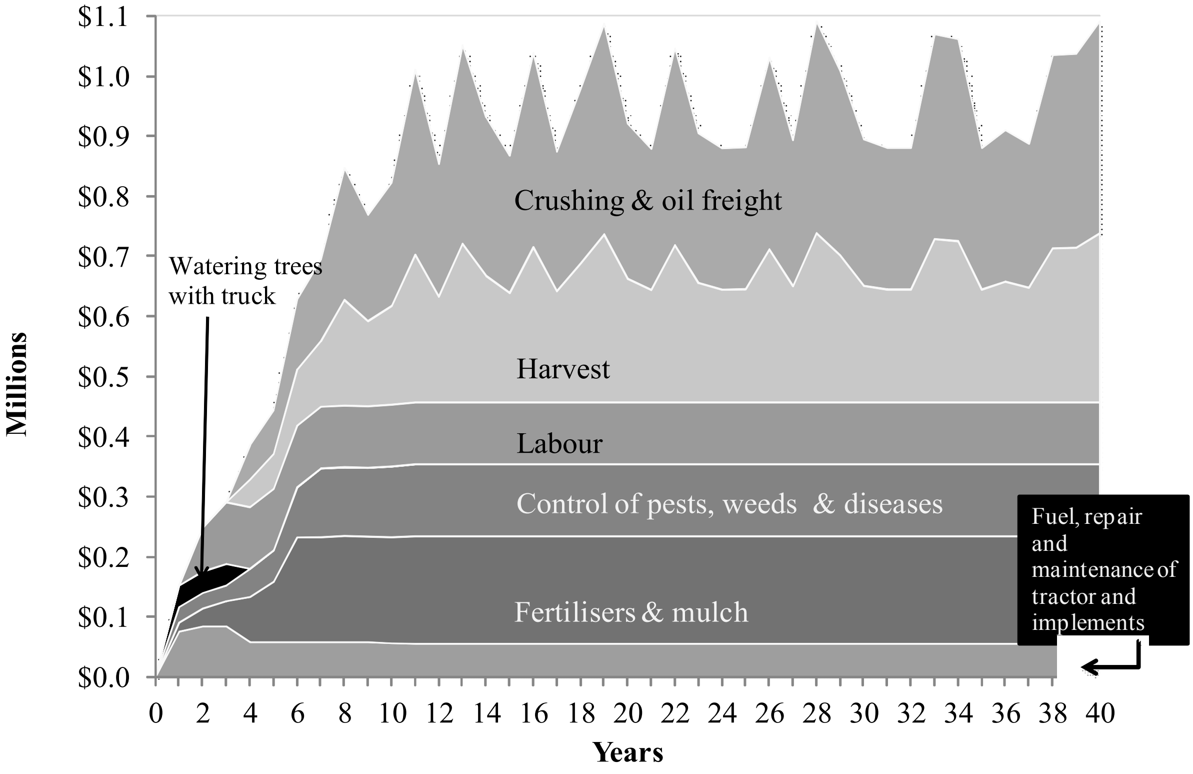


Figure 10-4 Annual operating expenses of pongamia plantation

Seed crushing, combined with the cost of freight of oil to a refinery, is the largest annual variable cost. It varies significantly between seasons as seed yield is directly affected by annual rainfall. It has a range of $57,000 to $352,000 between seasons and an average annual value of $254,000 and standard deviation of $74,000 (Table 10-10).

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[2] 500 hectare property with 357 trees per hectare

Harvesting is the second largest annual operating cost, with a range of $45,000 to $281,000 per season (Table 10-10).

Table 10-10 Range analysis of the main annual variable costs of operation of the pongamia plantation

Major variable cost categories	Plantation scale cost range $/year			
	Min	Max	Average	Std Dev
Harvest	$45,550	$281,435	$202,677	$59,237
Seed crushing and oil freight	$57,060	$352,554	$253,893	$74,207
Fertiliser & mulch	$14,850	$179,794	$163,496	$43,895
Weed, pest & disease control	$26,005	$119,670	$107,765	$28,626
Casual labour	$73,125	$102,375	$101,625	$4,684
Machinery fuel, oil, R&M	$55,718	$84,707	$58,085	$6,997

The nutritional requirements of the crop are assumed to be met by a combination of nutrients from commercial fertilisers and from mulch derived from by-products of the seed crushing plant. Average annual fertiliser cost of the plantation is close to $163,000. The seed meal and seed shells are assumed to be returned from the crusher back to the property. Pruned and mulched branches and twigs clipped by the harvester are also assumed to be returned to the plantation to avoid loss of nutrients.

The average cost of control of weeds, pests and diseases is estimated at $108,000 with the range shown in Table 10-10. Seasonal labour is hired at peak periods for pruning and cartage, at the hourly rate of $29 per employee, resulting in an average annual cost of close to $102,000. The costs associated with the fuel, oil, repairs and maintenance of machinery and implements (e.g. tractor and fertiliser spreader) are on average $58,000 per year. This fuel cost component was derived from market data for current fuel prices and estimated as described by Gargett (2011) and RACQ (2011). The methodology for estimating the machinery and implement variable costs as described in Khairo and Davies (2009) supplemented data from the “Guide for Tractor and Implement Costs” available on the website of NSW Department of Primary Industries.

10.9 Results and discussion

10.9.1 Delivered cost of oil

This section presents a discussion of the delivered cost of pongamia oil and the relative contribution from each of its components under the yield scenario of 20 kilogram (seeds in shell per tree per year). In this scenario, the total average annual production of the plantation (over a 40 year period) is estimated at close to 630,000 litres of oil with the average unit cost of oil estimated at $2.22 per litre.

This cost includes the cost of capital, variable costs and overheads. Capital expenses account for 30% of the delivered cost of oil as shown in Table 10-11. Another large cost component is the expense associated with wages, administration and power (26%). Fertilisers and management of weeds, pests and disease amount to 17% of the costs.

Seed crushing to extrude the oil and the delivery of oil with tank containers to a refiner account for 13% of the costs. Under the assumption of median yield of 20 kilogram of seed in shell per tree, the crushing plant will need to process 3,345 tonnes of seed per year, producing just over 0.63 million litres of oil per year in about 134 days of crushing operation. In years with higher than median production the plant will be required to operate longer during the year, which will reduce its cost per unit of oil.

Operating cost of the harvester and the associated cost of the on-farm cartage of seed, using a cartage bin hauled by a tractor, accounts for 10% of the cost. A minor component (5%) of the delivered cost is the cost of fuel, oil, repairs and maintenance of other plant and equipment not associated with above items.

Table 10-11 Breakdown of delivered cost of pongamia oil

Description of cost item	Per litre	Share
Land, fencing, harvester, crushing plant, tractor & other equip #	$0.66	30%
Wages, administration and power *	$0.57	26%
Fertiliser, weeds & pests *	$0.37	17%
Harvest of seed *	$0.22	10%
Crushing and freight of oil to processor *	$0.28	13%
Fuel, oil, repairs & maintenance *	$0.12	5%
Total costs	$2.22	100%

*Key: # item refers to a capital expense and * items refers operating expense.*
(Assumes 20 kg seed per tree per year).

The estimate of the average cost of production of $2.22 per litre requires careful interpretation. It must be used with caution and in conjunction with other summary financial and production indicators for it to be useful for decision making. It was derived from estimates of Equivalent Annual Value (EAV) of each cost item. EAV is an estimate of the annual value of each item over the life span of the plantation, based on the discounted present value of the item across the project life (40 years). It may be expressed as the discounted average annual value of the item (Peirson et al 2002, Zhang & Pearse 2011). The pongamia enterprise will experience very high cost of production per litre of oil at the beginning of the project and the cost will decline over time as the plantation matures and trees come into full production. This is similar to many fruit and nut orchards.

The preliminary analysis of the delivered costs of pongamia oil reported in Murphy et al (2012) was conducted by the author of this chapter. Since then a number of amendments have been made to the values of key parameters. Furthermore, data and information previously unavailable has prompted a review of some key assumptions about the growth and yield of the tree.

Significant differences between the analysis reported here and the economic analysis in Murphy et al (2012) include:

- The annual median yield range per mature tree has been revised to between 20 and 80 kilogram of seed in shell;
- Planting density has been reduced from 500 trees per hectare to 357 trees per hectare based on the recommended planting design of a 7 metre by 4 metre spacing which is more suited to a rain-fed grove or plantation.
- Purchase cost of land has been included in this analysis, whereas in Murphy et al (2012) the analysis accounted for foregone net income from reduced livestock carrying capacity of the land under pongamia. This is known as the opportunity cost of land. The latter approach is suited to a situation where the purchase of land is not necessary and the current land holder is only interested in weighing up the relative profitability of pongamia against the existing land use being grazing livestock. This is the case for plantation sizes of 5 to 20 hectares. However, for large plantations the purchase of land must be accounted for.
- The purchase of an additional 10 hectares of land has been included for the seed crushing and oil extraction plant, fuelling and loading yards, storage facilities, as well as the land required for parking, roads, laneways and driveways.
- The cost of fencing is another addition included to account for developing ten 50-hectare blocks of pongamia.
- Delivery of pongamia oil to processor gate has been added. The container delivery truck is assumed to be owned by a freight company and used by the pongamia enterprise on contract.

10.9.2 Analysis of alternative yield scenarios

The viability of a pongamia business will be closely linked to the growth and yield of the trees, for which there is currently very little data. Three alternative yield scenarios were examined to estimate the effect of seed yield on the delivered cost of oil. The three median yield scenarios were 20, 40 and 80 kilograms of seeds in shell per tree per year, with the results summarised in Table 10-12. These yields equate roughly to 7, 14 and 28 tonnes of seed in shell per hectare per year at the planting density of 357 trees per hectare.

Total delivered cost of oil is $2.22 per litre for the 20 kilogram per tree seed yield scenario as discussed earlier. This cost drops to $1.16 per litre in the 40 kilogram yield scenario and $0.64 per litre for the 80 kilogram scenario. At the highest seed yield scenario pongamia oil would be a very attractive feedstock proposition for manufacture of biodiesel under current market conditions. However, obtaining such a high yield from a rain-fed commercial pongamia plantation has not been reported by any credible sources.

Table 10-12 Components of the delivered cost of pongamia oil under three yield scenarios

	Median yield kg/tree/year		
Cost item	20	40	80
Land, establishment, harvester, crusher,… #	$0.66	$0.34	$0.18
Wages, administration and power ^	$0.57	$0.28	$0.14
Harvest of seed *	$0.22	$0.11	$0.06
Fertiliser, weeds & pests *	$0.37	$0.19	$0.10
Crushing and freight of oil to processor *	$0.28	$0.18	$0.13
Fuel, oil, repairs & maintenance ^	$0.12	$0.06	$0.03
Total delivered cost of oil per litre	$2.22	$1.16	$0.64

*Key: # denotes capital costs, * denotes variable annual operating costs and ^ denotes overheads or fixed annual operating expenses. Variable annual costs vary by the size of the harvest.*

The cost items with the greatest volume sensitivity are the capital expenses, overheads (consisting mostly of salaries and wages of employees), and the expenses associated with harvesting, and crushing operations. The impacts of these costs (on a per litre basis) are significantly reduced if the trees yield 40 to 80 kilogram of seed in shell.

10.9.3 Projected oil price scenarios

In the preceding sections, estimates of expenses incurred in the production of pongamia oil were described and discussed. They are essential in estimating the costs incurred in establishing and running the business. To estimate the profitability and return on investment, a realistic stream of revenues must also be estimated. Calculating expected revenues from the pongamia enterprise requires the use of plausible projections for the value of pongamia oil from the first harvest to the end of the life span of the analysis. This requires projection of one or more scenarios for the price of oil in the biofuels feedstock markets.

Most energy and fuel analysts informed by data from credible international energy agencies agree that the price of petroleum, and by extension biofuels, are likely to rise in the next few decades (IEA 2011, Graham et al 2011, Gargett 2011). These trends were used to construct three price scenarios for pongamia oil, which were considered plausible for the Australian market over the next four decades (Figure 10-5). These were used for estimating the revenues from the sale of pongamia oil.

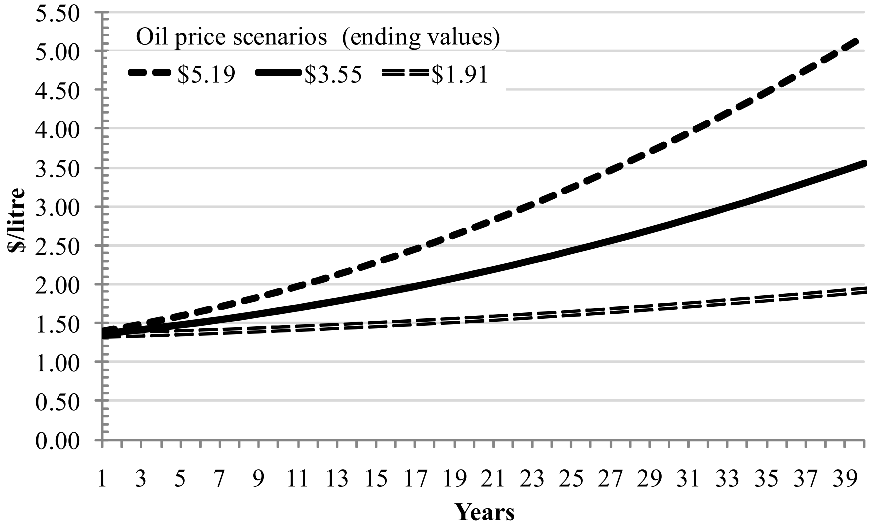

Figure 10-5 **Three projected pongamia oil price scenarios**

The price of oil received by the grower is assumed to be its value delivered to the gate of the refinery or processor. In other words the price includes transport cost of a tanker paid by crusher to have the oil delivered to a refiner. The price in the first year of the plantation was assumed to be $1.34 per litre for all three scenarios. In the first price scenario, the price reaches only $1.91 per litre by year 40. In the second scenario the ending price is $3.55 per litre. In the third scenario price reaches $5.19 per litre in year 40. This escalation in price captures the predicted price rise in fossil fuels and excludes any CPI inflation.

10.9.4 Cash flows and profitability of the plantation

This section considers the profitability and cash flow of the plantation and crushing plant. Figure 10-6 shows the cash flow of the enterprise under the assumption of median seed yield of 20 kilogram (7 tonnes per hectare) and a delivered price for pongamia oil that rises steadily over a 40 year period, from $1.34 to $3.55 per litre.

Revenues are shown as bars with positive values above the horizontal axis and the expenses are those below that axis. There is significant variability from one year to the next. This is associated with the variable rainfall and its impact on crop yield. The larger than average expenses in years 18 and 19 and again in years 33 and 34 are associated with the cost of replacement of major machinery in the crushing plant and the cost of purchase of a new harvester.

The plantation is capable of supporting livestock grazing between the trees once they are established and the revenues shown in Figure 10-6 reflect joint use of the land for pongamia and sheep. Sheep income is expressed as net revenue (i.e. after costs) and it is a minor component of revenue of the plantation land. The average annual net revenue from sheep is $25,799, with a low of $1,212 and a high of $133,699 per year. This large variation reflects historical fluctuations in the sheep industry for this region, caused mainly by a combination of rainfall (which affects the carrying capacity of pastures) and prices of wool and meat.

Income from the sale of pongamia oil is the product of the oil yield each season and the price received by the grower for that oil. Oil revenues do not start until the first harvest in year 4. The small amounts of income prior to year 4 are the revenues associated with hay harvested and fed to sheep elsewhere on the property or sold off farm. Most of the annual variability in revenue is due to rainfall variability that effects both pongamia seed yield and pasture growth. Annual expenses include variable, fixed and capital expenses.

Cumulative net revenues are the sum of annual revenues less the expenses over the life of the project. The cumulative discounted net revenue NPV is the sum of discounted annual net returns accrued at each stage in the life of the plantation. Cumulative NPVs for each of the yield scenarios are shown in Figure 10-7. The small fluctuation in the cumulative discounted net revenue is due to variation in revenues as well as variation in expenses. The NPV of the project is $-4.85 million for the 20 kilogram yield scenario, $7.43 million for 40 kilogram and $32.00 million for 80 kilogram, as shown in Figure 10-7.

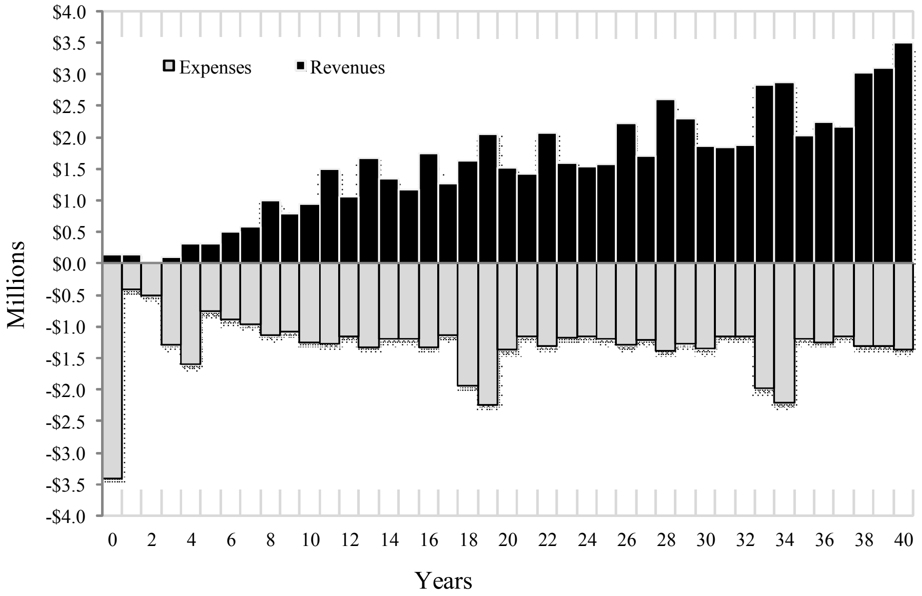

Figure 10-6 Sample cash flow for the pongamia business

The summary statistics of the profitability and cash flow of the plantation are shown for each of the yield scenarios in Table 10-13. Under the 20 kilogram yield scenario the project NPV is negative, indicating net loss of $4.85 million after 40 years, and the plantation does not produce a return on investment. This is equivalent to a loss of close to $10,000 per hectare. The equivalent annual value (EAV) of this NPV is a loss of $714 per hectare per year. EAV is an estimate of annual value of each expenses item over the life span of the plantation based on the discounted present value of the expense item across all the years. It may be expressed as the discounted average annual value of the expense item (Peirson et al 2002, Zhang & Pearse 2011).

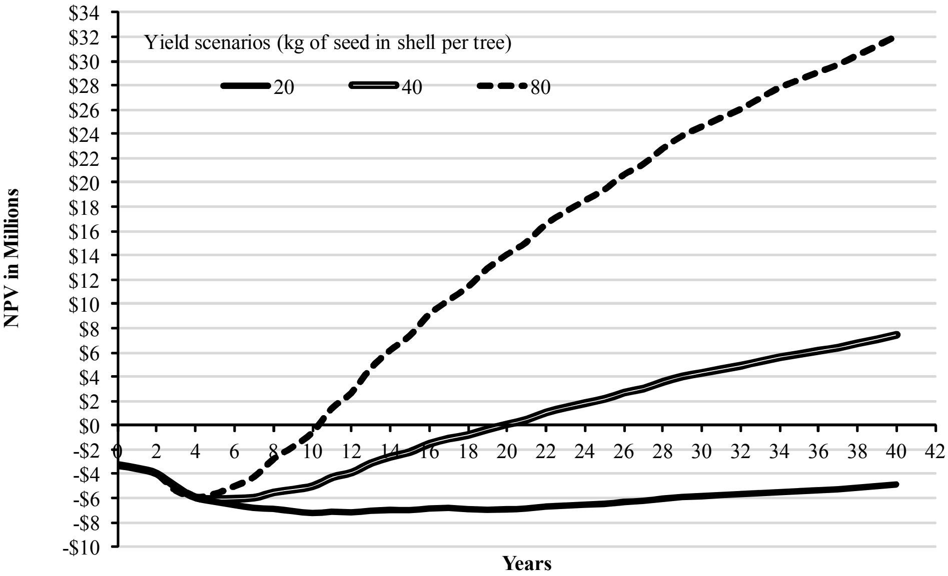

Figure 10-7 Discounted cumulative net revenues of the pongamia plantation

In the 20 kilogram per tree scenario peak debt is $7.18 million and it occurs in year 10. This is the highest discounted cumulative cash deficit in the life of the plantation under the yield, price and cost assumptions used for this scenario. In this scenario cash flows do not become positive until after year 11 onwards. Payback period, the year when the discounted cumulative cash flow of the project becomes positive, is not reached in this yield scenario.

Under the higher yield scenario of 40 kilogram of seed in shell per tree, the before tax IRR of the pongamia project is 11%, with an NPV of about $7.4 million or profit (discount net surplus) of about $15,000 over the 40-year life of the plantation. The EAV is just over $1,000 per hectare per year. Under this scenario the pongamia enterprise has a peak debt of $6 million incurred in year 5, the first positive cashflow is experienced in year 6 and payback is achieved by year 20.

In the 80 kilogram scenario, the highest yield assessed, the project provides a pre-tax IRR of 20%. The NPV is over $29 million, equivalent to about $62,000 of accumulated profits per hectare over 40 years and the EAV is just over $4,700 per hectare per year. Under this yield scenario peak debt remains at around $4 million but the higher revenues associated with larger volume of oil offset the cost of production, resulting in higher profitability and an earlier positive cash flow stream.

Table 10-13 Key financial indicators of the pongamia enterprise under each of the yield scenarios

Financial indicators	Unit	Seed yield (kg/tree/year)		
		20	40	80
NPV (whole property 510 ha)	$M	-4.85	7.43	32.01
IRR	%	N/A	11%	21%
Peak debt	$M	7.18	6.05	5.87
Peak debt	year	10	5	4
Payback period	year	N/A	20	11
Positive cashflow years	year	11	6	5
NPV per hectare of property	$/ha	-9,517	14,574	62,756
EAV	$/ha/year	-714	1,093	4,707

10.9.5 Sensitivity analysis

There are major uncertainties associated with the profitability of this hypothetical pongamia project. Preceding sections have shown that tree seed yield and price of oil are the least certain economic elements of this enterprise. Establishment and operating costs too are not well known but they are better known than tree seed yield and price of pongamia oil. Providers of machinery, equipment, merchandise and services for establishing, maintaining and harvesting a pongamia plantation are likely to be similar to those that service fruit and nut orchards. These industries are mature and the accumulated experience and skills base in such industries means that they are probably operating efficiently.

A sensitivity analysis was conducted to examine the potential impact of price and yield parameters on the viability of the pongamia business

The seed yields considered were 20, 40 and 80 kilogram of seed in shell per tree per year. The price scenarios considered were $1.91, $3.55 and $5.19 per litre of pongamia oil delivered to a refiner. Table 10-14 summarises the financial viability of the business for these yield and price scenarios.

A combination of the lowest yield and lowest oil price are not sufficient for the pongamia enterprise to achieve positive cash flows until year 13 and the project will lose more than $8 million over a 40 year period. The combination of a yield of 20 kilogram of seed per tree and oil price of $3.55 per litre is also not an attractive investment proposition with an NPV of $-4.85 million (a loss). On the other hand at the highest yield and price scenario, the pre-tax return on investment is 23% with a payback period of 10 years.

If low global petroleum stocks and climate change policies that are favourable to biofuels lead to a pongamia oil price of $5.19 per litre, the plantation shows a pre-tax return on investment of 6% under the yield scenario of 20 kilogram per tree. However, even at this high price, a yield of 20 kilogram is not enough to generate the revenues that will offset the cost of production, resulting in loss of close to $1.4 million.

Table 10-14 Sensitivity analysis for different price and yield scenarios

Annual median seed yield (kg/tree)	Key financial indicators	Unit	Price of oil per litre in year 40		
			$1.91	$3.55	$5.19
20	NPV	$M	-8.26	-4.85	-1.38
	IRR	%	N/A	N/A	6%
	Peak debt	$M	8.36	7.18	6.90
	Peak debt	year	35	10	10
	Payback period	year	N/A	N/A	N/A
	Positive cashflow	year	13	11	11
40	NPV	$M	0.62	7.43	14.38
	IRR	%	8%	11%	14%
	Peak debt	$M	6.11	6.05	6.00
	Peak debt	year	6	5	5
	Payback period	year	35	20	16
	Positive cashflow	year	7	6	6
80	NPV	$M	18.37	32.01	45.90
	IRR	%	18%	21%	23%
	Peak debt	$M	5.91	5.87	5.83
	Peak debt	year	4	4	4
	Payback period	year	12	11	10
	Positive cashflow	year	5	5	5

N/A: Not Achieved

10.9.6 Break-even analysis

The question that potential investors and those concerned about the development of pongamia industry may well ask is: what is the break even yield or price for pongamia? In other words at what yield might the plantation project cover its costs of establishment and operation. That is, at what price or yield does the project produce a zero NPV? These are the yield and price values above which the plantation will be profitable.

The result of breakeven analysis summarised in Table 10-15 shows that if the oil price was $1.34 per litre at the beginning of the project and reached $3.55 per litre by year 40 then a median yield of 28 kilograms of seed per tree, or 10 tonnes per hectare, would cover the cost of production. At the higher price of $5.19 per litre a median seed yield of 22 kilogram of seed per tree, 8 tonnes per hectare, would be required for the revenues (income) to breakeven with the costs of establishing and running the plantation. It is worth reemphasizing that at these yields the pongamia enterprise will break even with its cost of production without making a profit for its owners and investors.

If only 20 kilogram could be harvested per tree (7 tonnes per hectare) then the oil price starting at $1.34 per litre in the first year of the operation and ending at $6.00 per litre in the 40th year of the plantation would be necessary for the project to breakeven. However, at 80 kilogram per tree the costs are outweighed even under the current oil prices without any increase in future oil prices.

Table 10-15 Breakeven yield of pongamia under three price assumptions

Price ($ per litre of oil in year 40 after starting at $1.34 per litre)	$1.91	$3.55	$5.19
Breakeven yield (kg of seed in shell per tree per year)	39	28	22
Breakeven yield in tonnes per ha per year (at 357 trees/ha)	14	10	8

Table 10-16 Breakeven price of pongamia under three yield assumptions

Yield (kg of seed in shell per tree per year)	20	40	80
Yield tonnes per hectare per year (at 357 trees/hectare)	7	14	29
Breakeven price ($/l of oil by year 40)	6.00	1.90	<1.30

Key : < indicates that even if the price in the next few years was less than current prices the revenue from the plantation will break even with its cost of production.

This type of analysis can assist decision makers who are investigating the viability of investments in pongamia to identify the key uncertainties and their relative contribution to the viability of the project. Investors will differ in their attitude to risks and uncertainties in plantation projects. Identifying the type of decision rule to use and selecting the relevant information to be brought to bear on the choice being made is an essential part of sound investment analysis. It is particularly important to account for the impact of uncertainty on the profitability of a project by conducting a range analysis of the uncertain production parameters rather than adding risk to the discount rate (Pannell 1997, Peirson et al 2002, Zhang & Pearse 2011)

10.10 Conclusions

The purpose of this study was to make a positive contribution to priority setting in research and development programs that aim to improve commercial prospects of pongamia in Australia. The key economic parameters of pongamia oil production were investigated, with particular emphasis on tree seed yields and prices for pongamia oil. It is concluded that before pongamia can be considered a commercially viable source of feedstock for biodiesel in Australia, the uncertainties that exist about achieving adequate quantity and consistency of seed yield in commercial rain fed plantations must be resolved.

Through scenario analysis, a range of oil prices and seed yields were considered in this study. Under one cost structure and planting density assumed in this study, the break even yield is close to 28 kilograms of seed per tree per year. This is the median yield if the price of oil increases from its current value of close of $1.34 per litre to $3.55 per litre by the 40th year in the life of the plantation. If it is assumed that the price paid for oil rises only to $1.91 over 40 years, the break even yield is 39 kg/tree/year. A higher yield again will be required to move past the breakeven point and actually achieve a return on investment for the plantation and associated equipment.

There are three important contributors to the viability of the pongamia enterprise – the seed yield per tree, price per litre paid for the extruded oil and the combined cost of production of plantation and the seed crushing plant. Little is known about the biological performance of this tree in Australia. This study has shown how important yield is to the financial viability of a commercial pongamia plantation. It is possible that in practice some of the capital and operating expenses may end up costing less than those assumed in this analysis. However, marginal improvements to these costs are unlikely to make the plantation profitable if the tree seed yields remain at the low end of the scale assumed here.

At the current stage of development of pongamia, research and development is more likely to be effective if directed to improving the seed yield of pongamia than to improvement in cost structure of the plantation and marketing of oil.

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11. Supply and delivery of grasses

11.1 Summary

Cereal crop residues and dedicated grass crops are both potential sources of biomass for bioenergy. If a bioenergy plant has a shortfall in biomass supply, crop residues and grasses can be grown (subject to seasonal conditions) and supplied within a few months. Subject to availability, pricing and commercial terms, they may also provide dedicated, long-term supply to specific bioenergy plants.

The price of biomass from residues of cereal grain crops (straw) and grass crops depends on their production and transport costs. It also depends on the returns that producers of straw and grass expect from alternative markets for the biomass. In the case of a grass crop the opportunity cost of producing the biomass is also affected by alternative uses of the land for other agricultural commodities such as grain, meat, wool and woody biomass.

The analyses reported here focus on cereal crop straw and grass grown in the 450-600 mm annual rainfall zone of broadacre agricultural regions of southern Australia. Input data for these analyses are from the southern region of Western Australia, although the findings are broadly applicable across southern Australia. For both types of biomass, estimates of the delivered cost utilise data from industry sources and published reports.

The delivered cost of cereal straw biomass (with moisture content of 10 to 14%) is estimated to be within a range of $53 to $138 per tonne. At present, on the majority of cereal growing properties in Australia, the bulk of straw is not harvested for sale and is retained as standing stubble in the field. Published reports indicate little economic value in the use of cereal straw as paddock feed for grazing livestock due to its poor nutritional value.

In similar farming systems, the delivered cost of grass biomass (with moisture content of 12 to 14%) as bales is estimated to be in the range of $132 to $267 per tonne. Growing this biomass crop displaces other crops or pasture and it is necessary to achieve comparable profitability with those alternative land uses. This is the price range that commercial growers are likely to find acceptable and competitive with the net returns they achieve from typical agricultural land uses incorporating wheat, canola and pasture for grazing livestock.

11.2 Cereal crop residues

Residues of cereal grain crops are a potential source of lignocellulosic material for bioenergy production (Sultana et al. 2010). Cereal crops in Australia include wheat, barley and oats and these three crops represent 90% of Australian national annual grain production. There are significant quantities of cereal straw in Australia that are potentially available to be harvested as bioenergy feedstocks. The greatest concentrations of cereal straw are in southern Australia. There is large seasonal and regional variation in cereal crop production which affects availability of grain and straw (Warden & Haritos 2008, O'Connell et al. 2007, Herr et al. 2011, Simon et al. 2010, Farine et al. 2011, McEvilly et al. 2011, Rodriguez et al. 2011).

In this study the term straw is used to describe that proportion of the cereal crop residue that can be harvested and exported off farm. The term standing stubble is used for the part of the cereal residue that is left attached to the soil by the root systems. Herr et al (2011) estimated the amount of harvestable straw on a national basis. Their estimate allowed for a minimum cutting height of 12.5 centimetres and retention of one tonne per hectare of stubble in southern Australia for the purpose of providing soil cover to prevent erosion. Stubble retention also improves soil structure via incorporation of organic matter. There are, therefore, around 21 million tonnes of straw available for harvest per year on average. Seasonal variations, mostly caused by rainfall and grain price, can cause the annual availability of straw to be as high as 39 million tonnes or as low as 4 million tonnes.

The estimate for an average of 21 million tonnes may be higher than that which would actually be realised. Consultation with cereal growers indicates that in practice they are unable to get an average cutting height below 20-25 centimetres. The unevenness of the paddocks is one major reason for harvesting height being higher than 12.5 centimetres. The other reason is the preference of some growers for standing stubble cover of up to 1.5 or more tonnes per hectare attached to soil, to ensure that a reasonable protective soil cover still exists in autumn after some decay of stubble over summer (Herr et al 2011).

Currently, some cereal straw is harvested for animal bedding in Australia, but the vast majority is retained in the paddock as part of a minimum tillage farming system, or is grazed or burnt. Quantities of some of the straw baled in Australia in recent years can be estimated from data reported in Martin (2009). For instance between the 2002-2003 and 2006-2007 seasons an average of 83,300 tonnes of cereal straw was exported from Australia, mainly to Japan. Australian feedlots used an additional 80,000 tonnes of cereal straw in the 2003-2004 season. Table 11-1 shows the amount of straw exported or used for composting for mushroom production, animal feed, bedding and housing.

These estimates of current level of utilisation of straw appear very small from the perspective of potential annual supply at the national level. However, from a local or regional perspective, the supply and demand profile for straw biomass could be significantly affected if a bioenergy plant required 250,000 tonnes or more of biomass per year. For instance, in Western Australia, Hill et al. (2005) estimated that the potential area of annual cropping in the high rainfall zone of south-western Australia is around 2.1 million hectare. Assuming that close to 80% of this area could be in cereal grain production with an average yield of 2 tonnes per hectare, there is potential for production of 1.3 million tonnes of cereal straw that could be sustainably removed for use as bioenergy feedstock. A processor requiring a quarter of million tonnes of straw biomass will require 20% of this potential production in an average year and up to 50% in low rainfall seasons.

Table 11-1 Current level of utilisation of cereal straw in Australia

Straw Use	Estimated consumption (tonnes/year)
Export – for feeding and bedding	70-80,000
Composting for mushroom production	70-75,000
Feeding	30-100,000
Bedding	20-50,000
Housing	4-5,000
Total	194-310,000

The cost of biomass can be a significant proportion of production costs of bioenergy (Mani et al. 2006). In this section the focus is on estimating the cost of harvesting and delivering cereal straw as a feedstock for bioenergy production from broadacre dryland farming systems in the 450-600 mm rainfall zone. The analysis accounts for the costs of collection, baling and delivery as well as costs such as costs associated with export of nutrients (Miranowski & Rosburg 2010). Except for nutrients, the cost of the other agricultural inputs (such as herbicides) required to grow the cereal crop are not attributed to the cereal straw because they are assumed to be required for production of grain whether or not the straw is used for bioenergy.

In Australia, the price of the small proportion of the cereal straw that is baled and sold off farm (<3%) has, in the recent years, ranged from $80 to $110 per tonne. This price range was estimated from information provided by growers, traders and suppliers of straw and from review of published research (Ann Noakes of Glenbraewa in Narrogin pers. comm., 15 October 2011; Steve Blacker from Logan Contracting pers. comm., 15 October 2011; Rodriguez et al. 2011). Between the 2002-2003 and 2007-2008 seasons, the average annual indicator price of cereal straw was around $100 per tonne (delivered excluding GST) (Martin 2009). Cereal straw bales have moisture content of 10–14% (Herr et al. 2011).

11.2.1 Management of cereal residues

Cereal grain crops such as wheat and barley are generally harvested with combine harvesters which collect the grain and some of the straw. Under normal operation the cereal grain harvester chops the straw into flowable size pieces, combines this with winnowed material for the grain stream, and discharges it onto the paddock from the back of the machine.

The terms stubble and straw do not have consistent definitions among researchers, farmers and the agricultural press. Grain farmers tend to think of stubble as straw still anchored to the ground by dead root systems in combination with loose or unattached straw delivered from the back of the harvester. Livestock farmers tend to define stubble as the material left behind after harvesting and potentially available for sheep feed, despite its low nutritive value. This study adopts the classification used by Herr et al (2011) with the following commonly identified parts of the crop:

- ***Above ground biomass***
  the whole plant from soil level up, including grain
- ***Crop residue***
  all the material left after the harvester has passed – namely stems, leaf sheath, leaf, rachis and glumes and any small amounts of unharvested grain or sound or shrivelled grain ejected by the machine (also called the non-grain biomass)
- ***Straw***
  the stem and the leaf sheath which surrounds it
- ***Stubble***
  the attached and unattached straw left after passage of the harvester
- ***Standing stubble***
  the part of the stubble still attached to the soil by dead root systems
- ***Chaff or cocky chaff***
  Chaff is the material in the head of a crop that is separated from the grain at harvest. It includes glumes, awns, rachis and rachilla and any small pieces of shattered leaf or straw material, excluding the main fraction of leaf and stem. Chaff contains the smallest particles produced in the harvest processing and growers refer to them as “fines”. Unless special equipment is fitted into the harvester only insignificant amount of the “fines” will be collected when straw is baled from windrows.

In harvesting systems where the goal is grain removal, farmers set the harvest height to optimise capture of grain and minimise throughput of straw. The amount of material passing through the machine affects the speed of harvest and fuel use. Cutting heights of 25 to 35 centimetres above the ground are common for wheat and barley crops (Herr et al. 2011). Reducing cutting height by 15 centimetres can increase fuel consumption by 6%. It can also decrease the work rate and prolong harvest time by 27%. This can lead to increased harvest cost by 16% in Australian crops (Green 1992).

Robertson (2008) reported that the obstruction of seeding implements by large cereal crop residue loads on paddocks in high rainfall zones, or in high rainfall seasons, remains a problem. Farmers need to reduce heavy cereal residue loads to facilitate seeding with tyned implements. A majority of growers in WA use seeders fitted with tyned knife points to minimise tillage. The fine knife points on seeders are prone to blockage when sowing into heavy crop residues. Farmers sometimes resort to burning heavy cereal residues to facilitate seeding (GRDC 2012). However, this has other undesirable effects: it leaves soils exposed to wind and water erosion; fires can be difficult and costly to control and can cause property damage (Flower & Braslin 2006). Residue burning does offer weed control benefits, especially where there is risk of herbicide resistant weeds (GRDC 2012). There may also be some benefits associated with the prevention of disease carry over (Herr et al. 2011). The alternative to in-situ burning or grazing is to bale and remove the straw. Removal of weed seeds in the chaff increases the benefits of residue baling.

One-pass grain and stubble harvest systems have been developed which deliver grain and large square bales of straw and chaff as separate streams of product. In a system known as the Glenvar Bale Direct System (http://www.glenvarbaledirect.com.au), the combine harvester tows a baler which bales the straw and most of the chaff fed directly into it via a conveyor from the rear of the harvester. This system is relatively new and is not widely used but appears to:

- save time, fuel and labour by combining the two major processes of harvesting and baling into a single operation;
- create clean, uncontaminated bales with less wear and tear on the baler, resulting in lower baler maintenance cost;
- collect up to 30% more straw than conventional baling by avoiding loss of material on the ground;
- capture the majority of the weed seeds, reducing weed populations in subsequent crops.

In this study, the analysis was confined to straw and chaff available from normal grain harvesting in which the harvest height is 25 cm as practiced by the majority of growers in Australia (Herr et al, 2011). Two production scenarios for straw bales are examined.

1. Two pass scenario in which grain harvest is a separate operation to the straw baling operation. In this scenario, the baling of straw is a separate operation conducted by a hired contractor. This would require some minor modification to the grain harvester, lifting out or disengaging the straw chopper and spreader. Baffles can be installed to concentrate the straw to a narrow strip as it discharges from the rear of the harvester. This method makes it possible to direct the straw, chaff and weed seeds to narrow ‘header trails’ or windrows. The narrow windrows are then readily baled after the completion of harvest using a conventional baling system (Herr et al. 2011).

2. One pass scenario in which the grain harvest operation is carried out simultaneously with the operation involving the baling of straw and some of the chaff. In this case, the harvester tows a baler using a drawbar which bales straw and chaff fed directly into it via a conveyor. In this scenario the harvester’s straw chopper is also disengaged. The baler is driven by a hydraulic motor using power from the combine harvester. It is assumed that this will place an additional load on the harvester and will reduce its speed in heavy crops, increase fuel use, and add to the repairs and maintenance cost of the harvester. On the other hand, this operation eliminates the fuel and labour cost of a separate baling operation and increases the biomass yield because it can bale chaff, which typically cannot be baled if the straw is windrowed onto the ground.

11.2.2 Retention of stubble for conservation of soil and nutrients

In southern Australian protection of soil from wind and water erosion over summer and autumn is necessary to maintain land productivity. Maintaining an adequate quantity of material not harvested (the stubble) for conservation of soil and nutrients sets a limit for the amount of straw available for bioenergy. One tonne per hectare for cereal crops and twice as much or more for pulse and oil seed crops is the minimum recommended cover as standing stubble at the end of autumn. Chaff and leaf material provide little protection to the soil, and generally are not considered useful in erosion control (Carter 2007). The residue should contain stems attached to roots in soil. Excluding livestock from the field makes it easier to maintain adequate levels of anchored material. Decay of residue over summer and autumn is increased by grazing and trampling, fire and cultivation, summer rain and the soil biota. To maintain these levels of ground cover it is necessary to leave behind an amount that, after allowing for grazing and decay over summer, will amount to about one tonne per hectare by the following April to June period in the southern region of WA (Andrew Moore pers. comm., 21 September 2011).

In the next section it will be shown that typical harvesting systems result in retention of about 1.7 tonnes per hectare of residue attached to soil, which is the standing stubble that is not removed by the harvest of straw biomass. This level of retention should minimise risk of erosion. It is also assumed that on paddocks where straw is removed, the farmer does not use the field grazing livestock. This should ensure that at least one tonne per hectare of straw is left attached to soil by the end of autumn in preparation for the following crop, which is the most conservative of the several approaches to retention outlined above.

11.2.3 Estimating yield of available straw

At harvest, the ratio of grain to total above-ground biomass of a cereal crop is called the Harvest Index (HI). The HI is around 0.36 for the most common wheat varieties used in Australia (Dunlop et al. 2008; Unkovich et al. 2010; Herr et al. 2011). The HI can be used to estimate the amount of crop residue left behind after grain harvest. The remaining crop residue is mainly straw with some chaff and other fine components.

When cereal crops are harvested the stems are cut at an average height of about 25 centimetres above the ground, leaving the standing stubble. The balance of the crop goes through the harvester where grain is separated and the straw and other residue components are discharged to the ground. The above ground component of cereal varieties grown in Australia typically consists of 36% grain, 8% chaff, 46% straw (nodes, internodes, and leaf sheath), and 10% leaf blades, on the basis of weight. Some of the leaf material containing the flag leaf and older lower leaves is quite fragile at harvest and is often fragmented in the process and becomes part of the chaff.

The harvesting process removes the heads containing the grain and an attached length of straw. These are passed to the threshing drums where the grain, rachis, glumes and small pieces of leaf and straw are separated from the larger straw and leaf material, which is then sent to the back of the harvester. Grain is separated from the other components by sieves and fans and is retained in the machine, while the chaff rejoins the straw to be ejected from the back of the harvester in ‘header trails’ or windrows.

At harvest, three main components are potentially available for collection:

- The grain
- The straw that is cut during the harvest operation and ejected from the back of the harvester
- The fine ‘chaff’ material that is the head material minus grain which also contains pulverised leaves and small bits of straw.
- The remainder is the uncut standing stubble containing the lower stems and any leaf material still anchored to the ground.

Herr et al (2011) estimated straw and chaff production at various grain yields from normal harvesting operations in Australia based on a crop height of 70 cm, cutting height of 25 cm, and HI of 0.36. Their findings are summarised in Table 11-2.

Straw and chaff yields used in this analysis are for the southern agricultural region of Western Australia with annual rainfall of 450-600 millimetres and are based on the yields reported by growers in Planfarm-Bankwest Benchmarks (2011). In this region the grain yield of wheat is about 2 tonnes per hectare when averaged over several recent seasons. The analysis reported here assumes that the amount of harvestable lignocellulosic material is based on a wheat crop with a grain yield of 2 tonnes per hectare, 1.4 tonnes per hectare of straw and 0.5 tonnes per hectare of chaff.

Table 11-2 Amount of cereal residue biomass available from wheat crops of different yields

Crop grain yield (t/ha)	Standing stubble (t/ha)	Cut straw (t/ha)	Chaff (t/ha)	Total non-grain biomass (t/ha)
1	0.8	0.7	0.3	1.8
2	1.7	1.4	0.5	3.6
3	2.5	2.1	0.8	5.3
4	3.4	2.8	1.0	7.1
5	4.2	3.4	1.3	8.9

Estimates are based on a wheat crop cut at 25 cm, based on a crop height of 70 cm and harvest index of 36%. Source: Herr et al. (2011).

11.2.4 Value of nutrients exported with cereal straw

If straw harvesting becomes a regular practice it will be necessary to replace the nutrients removed from the field by the export of straw, in order to maintain soil fertility. The requirement for replacement of nutrients will depend on soil type, nutrient history, crop rotation, nutrient availability and amount of product being exported.

Herr et al. (2011) estimated the rates of application of inorganic fertilisers that would be required to replace nutrients removed in a tonne of straw. They noted that whether full or partial replacement is required depends on many location-specific circumstances. They showed a wide variation in the range of nutrients typically found in cereal straw. For instance they reported that a tonne of wheat straw may contain from 2 to 10 kilogram of nitrogen, 0.2 to 1.5 kilogram of phosphorous, and 6 to 16 kilogram of potassium. On some fertile Australian soils, straw can be removed for several seasons without causing nutrient deficiencies, while on low nutrient soils, deficiencies may arise rapidly. This suggests that the nutrient balance associated with regular straw harvesting should ideally be considered on a case by case basis for each proposed region rather than relying on generalised figures. Falconer and Bowden (2007) estimated the amounts of nutrients and lime that are likely to be removed by harvesting of straw in WA. Their findings are similar to those estimated by Herr et al. (2011).

The cost of replacing the required nutrients used in this study is based on rates of application necessary to replace the range of losses reported by these researchers. Values are estimated at the current prices of fertilisers, as quoted by CSBP Fertilisers, a major manufacturer and distributor of fertilisers in Western Australia. The estimated cost of replacing nutrients exported by removal of cereal residues is between $13 and $42 per tonne of baled straw (see Table 11-3).

11.2.5 Baling, cartage, storage and delivery to processor

In the 2010 and 2011 seasons the cost of baling by contractors was $30-$40 per tonne in Western Australia and South Australia (Big Bale Co. in Woodanilling WA, pers. comm.; Rural Solutions SA 2010). In the one pass straw baling scenario, where grain harvest and straw baling operations are combined, it is assumed that baling costs are halved (i.e. 15 to 20 per tonne) because the baler does not require a tractor and the cost for a driver is shared with the grain harvester. In this scenario it is assumed that the farmer owns the baler. The upper and lower range for the estimated cost of baling in each scenario is shown in Table 11-3.

Zwer and Faulkner (2006) estimated handling costs of hay bales on the farm at $5 per tonne. Farm Services Victoria estimated the paddock to shed cartage of hay bales at $8 per tonne (FSV 2010). The on-farm cartage and handling costs used in this study are expressed in current values and are assumed to be between $6 and $9 per tonne.

Straw harvesting and baling in southern Australia matches the seasonal production cycle of grain crops and occurs between November and February. However operators of bioenergy plants require a reliable, year-round supply of biomass. To ensure this continuity of supply of straw biomass the bales will need to be stored for some part of the year and potentially between years. The storage of bales could take place anywhere from the farm to the processor. Biomass can be stored after harvest in several ways including on-farm open air, on-farm covered, or storage in a centralised, covered facility. Open air storage could be unprotected on the ground or on crushed rock or covered by reusable tarp or hard plastic cap. Covered storage could be provided with a pole frame structure with open sides on crushed rock or it could be an enclosed structure on crushed rock (Mirowski et al. 2010).

When considering cost of land and handling, it is likely that the storage at the farm is the most economical option. At the farm there is a choice between field storage of bales and storage in a shed (Liu, 2008). The loss in biomass is highest when biomass is left unprotected and lowest in the enclosed structure. Field storage of bales of straw avoids the cost of a storage structure or site preparation. The cost of field storage under a cover can be between 30% and 50% of storage in a shed (Taylor et al. 1995; Saxe 2007; Liu 2008).

There is loss of quality and quantity in straw during storage and it is higher for straw stored in the field. The amount of biomass lost during field storage depends on the duration of storage, rainfall, site drainage, bale density and the dimensions of the stack. The main costs associated with field storage of straw bales are labour, machinery, site preparation and the material used to cover the stack. Zwer and Faulkner (2006) estimated the cost of shed storage of oaten hay at $10 per tonne. For the purpose of this analysis the cost of storage was assumed to be in the range of $6 and $13 per tonne.

Estimates of the cost of delivery of straw bales by road transport were based on a range of sources. Transport contractors provided estimates of between $25 and $35 per tonne for a one-way, 100 kilometre delivery distance (Russell Lenehan from Logan Contracting pers. comm. & Jeff McKenzie from McKenzie &Co Transport, 15 October 2011). Some hay bale transporters indicated that they would be willing to charge lower than $10 per tonne for regular loads of short distances close to their home base. In this analysis a range of road transport costs is assumed, depending on the distance travelled. The range of one-way haul distance of 20 to 100 km is costed at $8 to $25 per tonne of baled straw, as shown in Table 11-3.

This analysis does not include the cost of farm manager's wages or a share of the fixed costs of farm operations. Fixed costs include overheads such as rates, licences, water, administration, electricity, gas, finance and insurance, as documented in Planfarm Bankwest Benchmarks (2011). These costs are omitted because straw production places a much smaller demand on the capital and human resources of the farm business than do production of grain and livestock. This operation is secondary to grain production and few managerial or financial resources are required in harvesting, baling and transport of biomass. A nominal grower profit margin of $5 to $10 per tonne has been included as an incentive, to encourage a reliable supply of biomass for future bioenergy producers (Brechbill, S & Tyner, 2008; Sultana et al, 2010).

11.2.6 Delivered cost of cereal straw bales

The delivered costs of cereal straw in large square bales are estimated to be between $68 and $138 per tonne for the two pass scenario and between $53 and $118 per tonne for the one pass scenario (Table 11-3). The one pass scenario is $15 to $20 cheaper because the grain harvest and baling processes are combined thus reducing some operating expenses (in the absence of actual data, no allowance has been made for the possibility of increased biomass yield due to chaff collected in the single pass operation). In both scenarios, the largest cost items are assumed to be the replacement of nutrients in straw and chaff exported with the bales, the cost of baling and the road transport cost.

Table 11-3 The range of likely costs associated with production and delivery of cereal straw

Cost items	Two pass scenario: Separate grain harvest and straw baling		One pass scenario: Combined grain harvest and straw baling	
	Lower Estimate $/t	Upper Estimate $/t	Lower Estimate $/t	Upper Estimate $/t
Nutrients replacement	13	42	13	42
Baling of straw	30	40	15	20
On farm cartage and handling	6	9	6	9
Storage	6	13	6	13
Grower profit margin	5	10	5	10
Transport to processor	8	25	8	25
Delivered cost of straw biomass	68	138	53	118

Baling costs will vary according to the number of bales produced each year. Further analysis could show the marginal costs of baling straw as compared with the underlying financing costs that most baling contractors face with their machines. As the largest cost component of the delivered straw, a greater understanding of this variable could be very helpful. Currently straw is an extra revenue source for hay baling contractors as it stretches out their baling period. An added complication here is logistics. Supplying a bioenergy plant with 50,000 tonne/year of baled biomass could require an entirely different set of price structures and dynamics for contractors that are used to baling just 5,000 tonne/year in a small area. Due to the scale required they will need to be dedicated to this task for several months and may bale straw for much less (Colin Peace Pers. Comm.)

11.3 Biomass from grass crops

Grasses are another potential source of lignocellulosic biomass for second generation biofuels and renewable electricity (O'Connell et al. 2007; Miranowski & Rosburg 2010; Farine et al. 2011; Graham et al. 2011). Native and introduced grasses could be grown and harvested using existing equipment, labour and capital on most farms in southern Australia. This section describes estimates of supply system costs for such a grass crop. The scenario examined is for a system where grass is cut and baled in large square bales and transported to a bioenergy facility. The conceptual framework for this type of analysis is described by Miranowski & Rosburg (2010).

Although the modelled scenario does not yet exist in Australia (Herr et al. 2012), the proposed supply chain is based on options available within present farm infrastructure and does not require substantial change, or capital investment for the operators along the supply chain. This section presents the production economics of a hypothetical grass crop grown in the south west agricultural region in Western Australia. This region has an annual rainfall range of 450-600 millimetres and includes some 3.7 million hectares of cleared freehold land of which only around 20 to 50 per cent is cropped. The remainder is typically under pasture to provide feed for grazing livestock (Hill et al. 2005).

Crops such as cereal hay and annual grasses typically produce more biomass than cereal grain crops. Typical yield of oaten hay achieved on farms in this region is estimated to be about 8 tonnes per hectare with moisture content of 10-14% (Zwer & Faulkner 2006). Under this yield assumption there is potential for production of about 5 million tonnes of grass biomass in the case study region if half of the land that is usually not planted to grain crops in the region is planted to grasses. This potential production is estimated after allowing for retention of 1.7 tonnes per hectare of standing biomass attached to the soil for the purpose of prevention of soil erosion. It can be reasonably expected that farmers will respond to opportunities presented by grass crops in the same way that they respond to other land use options. Adoption studies for other crops in Australia and elsewhere have reported that, in making their land use allocation decisions, farmers are primarily concerned about the profitability of new crops and their potential returns on investment (Abadi, Ghadim & Pannell 1999; Pannell et al. 2006; BR&Di 2008; Sherrington et al. 2008). A study has shown that farmers find it difficult to calculate the returns from energy crops due to uncertainty over costs, potential yields and prices (Sherrington et al. 2008). By contrast, farmers are well aware of returns from conventional crops and the prices and yields required for them to be profitable. Greater understanding of yields and costs, clear price signals, and acceptable prices to growers will all be required for grass biomass to become a feedstock for bioenergy. By accounting for the major costs of production of a grass crop, this chapter provides a guide to the range of prices that landholders may be willing to accept to grow, harvest and deliver the biomass.

Several factors are likely to affect the development of new grass crops. The key factor is the price that a bioenergy plant can pay for feedstock, which is influenced by prices paid for renewable energy, and also by the pricing of alternative sources of biomass. Annual grass crops can be integrated into crop-pasture rotations and land use sequences. A factor in favour of adoption of grass crops is that producers can employ the same production tools and techniques commonly used for production of hay.

Within rotational and agronomic constraints, farmers can readily switch their land use between production of grain crops, pastures for livestock, and production of biomass from grass crops. The land use change decision depends on the relative profitability of each crop and also the impact they have on subsequent land uses (Miranowski & Rosburg 2010). For instance, a grass biomass crop may reduce the profitability of subsequent cereal grain crops due to carryover of plant diseases from grasses to crops like wheat. For the majority of farmers, crop and pasture rotations are one of the key strategies in controlling grass weeds and root diseases of cereal grain crops (Abadi, Ghadim & Pannell 1991; Fisher et al. 2010; Herr et al. 2011).

The assessment reported here provides an estimate of the delivered cost of biomass from grass crops by using a methodology similar to that used for annual oaten hay crops published by various state government agricultural agencies, including Farm Services Victoria at the Department of Primary Industries (FSV 2010), Rural Solutions South Australia (Rural Solutions SA 2010) and reported by Zwer & Faulkner (2006). Calculation of the delivered cost of grass biomass requires estimates of yield and various costs such as establishment of the crop, harvest and delivery of the product (Miranowski & Rosburg 2010).

11.3.1 Yield of grass crop

Grasses of various species and varieties have been considered for production of biomass. They include wild sorghum, kangaroo grass, tall fescue, and ryegrasses (Farine et al. 2011; O'Connell et al. 2007). They range in harvestable yields from 5-12 tonnes per hectare, depending on rainfall, soil type and availability of nutrients, similar to those observed in hay crops (Bolger & Turner 1999; Mitchell 2002; Zwer & Faulkner 2006; Guest 2008; Bowman & Scott 2009; Chivers & Raulings 2009). A higher range of yields has been suggested by Graham et al. (2011).

Compared to introduced grass species, such as ryegrass, much less is known about production potential of the Australian native grass species in different agro-climatic conditions and edaphic situations. The limited available information for production of native grasses focuses on their ability to provide green feed for grazing ruminant livestock. Total annual biomass (herbage) production of between 5 and 10 tonnes per hectare has been recorded in research plots (Robinson & Archer 1988; Mitchell 2002; Chivers & Raulings 2009; Moore, 2012).

Ryegrass is one of the most vigorous of grass species in the modelled region, often included in the pasture swards because it produces a significant amount of spring growth (Mick Poole, pers. comm., 21 September 2011). Bolger and Turner (1999) found in pasture trials in the 400 to 700 millimetre annual rainfall zone of south-western of Western Australia that production rarely exceeded 12 tonnes per hectare.

Bowman and Scott (2009) summarised the empirical evidence for relationship between rainfall, water use and end of season dry matter production for annual pastures and grain crops. Water Use Efficiency (WUE) is a measure of the forage (biomass) or grain yield produced for each millimetre of water used (i.e. transpired) by a pasture. French and Schultz (1984a,b) developed a methodology for estimating water use efficiency in vegetative production of crops and pastures. In Western Australia production of annual pastures with high fertiliser inputs is around 30 kilogram of dry matter per hectare per millimetre of rainfall (Bolger & Turner 1999). Dry matter production for annual pastures can be in the range of 4 to 11 tonnes per hectare in the 400 to 500 millimetre annual rainfall zone, depending on the season, input levels and site characteristics such as soil type (Bowman & Scott 2009).

Zwer and Faulkner (2006) reported average oaten hay yields for selected varieties on several sites in southern Australia in the period 1998-2004. In areas with rainfall of between 375 and 500 millimetres the average yield was close to 9 tonnes per hectare. Where rainfall was over 500 mm rainfall yields of around 12.5 tonnes per hectare were observed. Results of research conducted by the National Oat Breeding Program reported by Zwer and Faulkner (2006) show average hay yields ranging from 9 to 12 for selected varieties of oats in Western Australia, South Australia and Victoria from 1998 to 2004.

Considering that yields achieved by farmers may not be as high as those observed in research trials, in this analysis, the biomass yield range is assumed to be 6 to 10 tonnes per hectare for a hypothetical grass crop with a moisture content, at harvest, of 12% to 14%. In this analysis, the harvested biomass yields of 6 to 9 tonnes per hectare are assumed to be achievable after allowing for retention of 1.7 tonnes per hectare of residue attached to the soils for protection against water and wind erosion.

11.3.2 Opportunity cost of biomass and farm land

There is currently no use of grass and straw for bioenergy in Australia. In the absence of a specific bioenergy market, the price of baled straw and grass in the fodder market may, at least in the short term, provide a reasonable proxy. Contact with traders indicated that baled cereal straw biomass, was traded in 2011 at a farm gate price of between $80 and $110 per tonne. The cereal straw market is small and is limited to fodder and animal bedding. Martin (2009) summarised the limited national statistics to show that the reported trade of baled straw for use by the dairy, equine, beef feedlot and export industries amounted to no more than 160,000 tonnes per year. The hay market is much larger and cereal hay production in Australia is 1 to 3 million tonnes per year. Total fodder production is around 6 to 8 million tonnes per year in Australia, which includes fodder made from pastures, cereal hay, straw and lucerne.

Table 11-4 shows a summary of the production costs, revenues and profit margins associated with growing oaten hay crops in Australia from 2004 to 2011. The average cost was around $90 per tonne and the lowest reported farm gate price was $80 per tonne for poor quality hay, straw or weather damaged hay (Zwer & Faulkner 2006). The highest price reported was $200 per tonne quoted by the Victorian DPI for irrigated oaten hay (FSV, 2010). The gross margin ranged from -$5 (a loss) to $111 per tonne.

Table 11-4 List of published examples of production economics of oaten hay

Location Unit	Yield t/ha	Sale Price $/t	Prod. Cost $/t	Profit Margin $/t	Year	Sources
National	8	80-135	85	-5 to 50	2006	RIRDC[1]
NSW	6	169	81	88	2011	NSW DPI[2]
SA	4	125	100	25	2010	SA DPI[3]
Vic	12	200	89	111	2010	Vic DPI[4]
WA	6	120	88	32	2004	DAFWA[5]

References for sources: 1 : Zwer and Faulkner (2006); 2: NSW-DPI (2011); 3: Rural Solution SA (2010); 4: FSV (2010); 5: DAFWA (2005)

11.4 Costs for production and transport

In this study, a range of costs has been estimated for the production and transport of grass biomass, as summarised in Table 11-5 below.

The cost of establishing the crop, including seeds, seed bed preparation, sowing, weed control, fuel, oil, repair and maintenance of the seeding gear is estimated at $19 to $31 per tonne. This is the average of the estimates for sowing costs provided by FSV (2009), NSW-DPI (2011), DAFWA (2005) and Zwer and Faulkner (2006) expressed in present dollar values. These costs are incurred on an area basis (i.e. per hectare of crop), thus reducing the cost per tonne if the crop yield is in the higher range estimate.

A significant expense in production of grass is the cost of replacing the nutrients removed from the field by regular harvest. Falconer and Bowden (2007) and Zwer and Faulkner (2006) estimated the amounts of nutrients removed in the production of straw and hay biomass in Australian farming systems. The major nutrients that are necessary to grow biomass crops on an ongoing basis are nitrogen (N), phosphorus (P) and potassium (K). Sulphur, calcium, magnesium and lime must also be replaced in small quantities in order to maintain soil productivity. The range of fertiliser application rates used in this study are based on replacing the nutrients exported by oaten hay crops as described in Zwer and Faulkner (2006) and Falconer and Bowden (2007). The cost of nutrients used in this analysis, including the expenses associated with cartage and application of fertilisers, is $42 to $81 per tonne of biomass. Crop yield, soil type, fertiliser and land use history and climatic conditions are some of the reasons for this variation in the rates of application of nutrients.

Table 11-5 Estimated value of factors of delivered cost of biomass for a grass crop

Production costs	Lower Estimate $/t	Upper Estimate $/t
Seed, crop establishment and weed control	19	31
Fertiliser to replace exported nutrients	42	81
Contract cutting, conditioning, raking	8	13
Contract Baling	30	40
On-farm cartage and handling	6	9
Storage	6	13
Fixed/overhead costs	7	11
Opportunity cost of land/foregone profit margin	7	43
Road transport	8	25
Total delivered cost of biomass	132	267

The cost of using a contractor to cut, condition and rake the grass crop is estimated at between $9 and $14 per tonne. The cost of this operation is usually incurred on the basis of per unit of land, estimated at an average cost of around $80 per hectare (Zwer & Faulkner 2006; Rural Solution SA 2010).

The cost of baling is usually charged by contractors on a per tonne or per bale basis. The baling cost range quoted by contactors, in 2011 dollar values, is between $30 and $40 per tonne (Big Bale Co in Woodanilling WA, pers. comm., 23 January 2012). This range is similar to estimates provided by Zwer and Faulkner (2006) and Rural Solution SA (2010). The costs for baling grass for bioenergy customers may vary from these amounts if a larger scale of operation provides unit economies.

Harvesting and baling of hay occurs between November and January in southern Australia. The crop production cycle of grass for bioenergy is expected to be similar to that of hay. Storage of this seasonal production will be necessary in order to provide bioenergy plants with a steady and reliable supply of biomass throughout the year.

The storage of bales on the farm or at a central location has been discussed in a previous section dealing with storage of cereal straw. The cost of storage was assumed to be in the range of $6 to $13 per tonne.

Farm Services Victoria estimated the on farm cartage cost of hay bales to a shed on the farm at $8 per tonne (FSV 2009). Zwer and Faulkner (2006) reported a $5 handling cost per tonne for hay bales. The range of $6 to $9 per tonne used in this study is based on minimal carting of bales within farms that are between 1,500 and 3,000 hectare. These estimates are similar to those reported for the USA (Taylor et al. 1995; Saxe 2007; Liu 2008).

Fixed and overhead costs of the farm are also accounted for in the cost of production of the grass crop. The farm's overheads or fixed costs include local government (shire) rates, licences, utilities (power and gas), administration, insurance and wages. These are costed at $67 per hectare or from $7 to $11 per tonne of biomass, for an average farm in the southern agricultural region of Western Australia (Planfarm Bankwest 2011).

A grass crop is likely to displace either other crops, such as wheat, canola or pulses, or a pasture that would be used for grazing livestock. Thus it is necessary to account for the profitability of alternative uses of the farmland. Inclusion of a profit margin in the cost of biomass reflects the opportunity cost for the farmland being used (Brechbill, S & Tyner, 2008; Miranowski & Rosburg 2010; Sultana et al, 2010). For the southern region of Western Australia, the average opportunity cost of farmland expressed in net operating surplus is $130 per hectare. Analysis of farm benchmark data, as reported by Planfarm Bankwest (2011), shows that there is a wide variation in profitability between years and among landholders. This variation is caused by factors such as climate, market, managerial skills and experience of the farmer, financial resources of the grower, soils type and farm size. When averaged across several seasons, the range of profitability is $65 to $260 per hectare. This is equivalent to $7 to $43 per tonne of grass depending on the yield of the grass crop.

Road transport cost for delivery of bales by contracted regional freight transporting firms was based on a range of sources. Transport contractors that were contacted provided estimates of $8 to $25 per tonne. The cost depends on the haulage distance from the farm to the processor, typically 20 to 100 km (one way), and also the volume and frequency or seasonal regularity of trips (Russall Lenehan from Logan Contracting pers. comm., and Jeff McKenzie from McKenzie & Co Transport pers. comm., 15 October 2011). Contractors indicated that it takes two hours to load and strap baled biomass loads, it takes another hour to unload. The average speed is 75-85 kilometres per hour with a B-double truck carrying 64 bales or 32 tonnes of biomass. Typical load trips are around six hours which is often costed at $130 per hour. Rural Solutions SA (2010) quoted a freight cost of $20 per tonne for a haulage distance of 100 km. Zwer and Faulkner (2006) assumed $15 per tonne for 100 km haul distance. In this analysis road transport is costed in the range of $8 to $25 per tonne of baled biomass.

After considering the costs of production, harvest and transport of biomass the delivered cost at a processor gate is in the range of $132 to $267 per tonne of baled biomass.

11.4.1 Marginal analysis

This is a not a whole-of-farm analysis, it is a marginal analysis. The economic framework uses an estimate of the likely range of the long run equilibrium price of biomass that producers may be willing to accept for the marginal or last unit of feedstock that they grow, harvest and deliver to al bioenergy plant (Miranowski & Rosburg 2010). The estimated delivered cost of biomass is the cost associated with allocation of land to production of biomass from one or two paddocks or fields of a farm – hence marginal analysis. As such, the analysis does not include a full capital budgeting exercise. Using the results of marginal analysis in this way enables the land holders to compare one land use against another.

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12. Sustainability & life cycle assessments

12.1 Summary

The development and operation of any new bioenergy plant must take into account the sustainability of that plant and its biomass supply chain. Assessment of sustainability can be a complex process, covering separate issues for economic, environmental and social sustainability. Disregard for these issues may lead to projects that purport to be environmentally beneficial but actually have damaging consequences, exemplified by the inappropriate development of some oil palm plantations for production of biodiesel at the expense of rainforests and peatlands in SE Asia. Fortunately in Australia there are large scale opportunities available that appear to offer a range of environmental and social benefits, in addition to commercial bioenergy. An example is the utilisation of waste biomass and tree planting as part of integrated farming in the wheatbelt.

Much of the current interest in bioenergy comes from its ability to produce energy with less greenhouse gas emissions than fossil fuels. International surveys of bioenergy for electricity production show that it can be as effective as other forms of renewable energy (wind, solar) in this regard. Current biofuels (using sugars, starches and oils as feed) can achieve useful reductions in GHG emission if developed carefully. Advanced generation fuels using lignocellulosic materials as feed can achieve major reductions in GHG emissions.

Assessment for sustainability may use general criteria that are relevant to bioenergy projects globally, however their application to each Australian bioenergy opportunity must focus on local data and local conditions.

12.2 Introduction

Discussion of sustainability generally considers three separate and important elements:

- Environmental
- Social
- Economic

A fully sustainable industry must accommodate prerequisites in each of these categories. One interpretation of this is given in **Error! Reference source not found.** below[1].

McBride et al[2] state that “Sustainability is the capacity of an activity to continue while maintaining options for future generations”. They note that each of the three elements above has a number of sub-elements that include:

• Economic	Prices, Market Access, Supply and demand, Natural resource accounting, Trade, Costs.
• Environmental	Greenhouse gas emissions, Air quality, Land use impacts (direct and indirect), Water quality and quantity, Soil health, Weeds and GMOs, Biodiversity and habitat, Other ecosystem services.
• Social	Food security, Energy security, Physical security and health, Labour rights, Cultural and spiritual values, Participation, Property rights.

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[1] Dr Daniel Inman – Biofuel Sustainability Analysis. Presentation given at Oak Ridge National Laboratory, 26 July 2012. http://www.ornl.gov/sci/ees/cbes/forums.shtml

[2] McBride AC et al – Indicators to support environmental sustainability of bioenergy systems. Centre for Bioenergy Sustainability, Oak Ridge National Laboratory, January 2011. http://www.ornl.gov/sci/ees/cbes/forums/Slides_Jan11.pdf

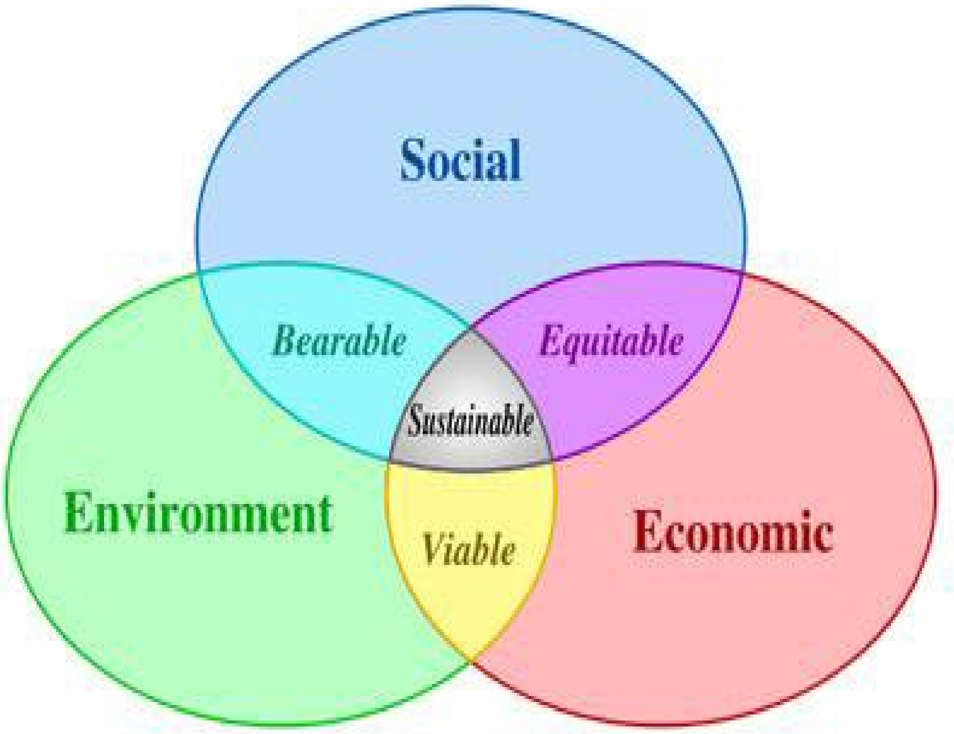

Figure 12-1 The interaction of sustainability prerequisites

Importantly, the interpretation of these sub-elements may vary by location, scale, culture and time. Wilbanks[3] has commented that: “Sustainability is a trajectory, not a state. Sustainability can take the form of multiple pathways, each associated with winners and losers: who decides?”

Some of the major issues with regard to the sustainability of bioenergy are discussed below.

12.3 Economic sustainability

Bioenergy projects are usually capital intensive; they involve significant upfront costs to build sophisticated equipment that converts biomass into heat, electricity or biofuels. To take place these projects must attract investment, which requires that they be economically sustainable, generating consistent cash flows over many years to provide a satisfactory return on capital.

12.3.1 Valuing environmental benefits

Bioenergy, like other forms of renewable energy, is often more expensive than current fossil fuel alternatives when measured purely on cost per unit of energy generated. While there are examples of bioenergy being developed purely as a competitive source of energy, there are many cases where the environmental benefits (particularly greenhouse gas mitigation) are a major justification for a bioenergy plant to be built. A value may be placed on those GHG benefits in order to encourage private investment. In Australia there are currently several schemes that provide financial support for commercial-scale bioenergy projects:

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[3] Wilbanks T – Perspectives from sustainability science about energy sustainability. Centre for Bioenergy Sustainability, Oak Ridge National Laboratory, March 2011. http://www.ornl.gov/sci/ees/cbes/forums/Slides_Mar11.pdf

- The Renewable Energy Target[4] is an Australian Government scheme to support the generation of renewable electricity. Under this scheme electricity made from eligible sources of biomass qualifies for financial credits that help to provide investors with returns sufficient to justify construction and operation of new bioenergy generation facilities.
- The Cleaner Fuel Grants Scheme[5] is operated by the Australian Taxation Office to provide incentives for the manufacture of eligible biofuels.
- The Ethanol Production Grants Program[6] is managed by Ausindustry and supports production and deployment of ethanol as a sustainable alternative transport fuel in Australia.

The carbon price in the Australian Government's Clean Energy Future program does not initially provide financial incentives for bioenergy. In the future, financial recognition of the benefits of bioenergy (and other forms of renewable energy) are likely to transition from dedicated schemes, such as those above, to a general carbon price.

12.3.2 Support for new industry development

Industries generally become more cost-effective as they grow and mature. This has been demonstrated over many decades for metallurgical and processing industries around the world[7] and has also been found with renewable energy. For example, historical cost reductions for photovoltaic (PV) solar cells have been assessed at 22% for every doubling of installed capacity worldwide, and further cost reductions are expected over coming years[8,9]. At present, electricity from PV cells is more expensive than electricity from many other sources and large scale financial support has been applied world-wide to encourage corresponding investment of private capital and help the industry grow and mature. There is a reasonable expectation that, over time, electricity from PV solar cells will become more competitive with conventional electricity and less reliant on subsidies and grants. This target of greater competitiveness and eventual financial independence helps to justify the financial assistance recently and currently provided.

The same argument can be applied to many forms of bioenergy. For example, support for biofuels now should lead to more cost effective biofuels production in future, at which time the need for support would be reduced. Furthermore, commercial demonstrations of advanced biofuels technologies over the next few years will reduce the risk profile for these technologies, improving access to larger pools of funds and lower rates of return. This will also improve the financial viability of projects and reduce the need for longer term government support.

12.4 Greenhouse gas emissions

Bioenergy is one of many forms of renewable energy that are being used to reduce mankind's greenhouse gas emissions. Bioenergy must be capable of achieving greenhouse gas reductions to justify industry support.

Bioenergy achieves GHG reductions in a different way to renewable energy technologies such as wind and solar. During the combustion of biomass or biofuels, carbon dioxide is created and released into the atmosphere. The carbon dioxide released during combustion is matched by carbon dioxide captured from the atmosphere through the photosynthetic process[10] that allows the feedstock to grow. Sustainably grown feedstock is therefore an important element of any bioenergy project. Many forms of bioenergy have been shown to provide greenhouse gas reductions that are comparable with other

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[4] http://www.climatechange.gov.au/ret

[5] http://www.ato.gov.au/businesses/content.aspx?menuid=9955&doc=/content/00128216.htm&page=3&H3

[6] http://www.ret.gov.au/energy/energy_security/fuels/alt-trans-fuels/alt-fuels/epg/Pages/epg.aspx

[7] Brennan D. Process industry economics – and international perspective. Published by the Institution of Chemical Engineers, 1998. ISBN 0 85295 391 7

[8] Hearps P et al. Renewable Energy Technology Cost Review. Melbourne Energy Institute, May 2011. http://www.earthsci.unimelb.edu.au/~rogerd/Renew_Energy_Tech_Cost_Review.pdf

[9] Solar Energy Technologies Program: Multi-year Program Plan 2007-2011. US Department of Energy. http://www1.eere.energy.gov/solar/pdfs/set_myp_2007-2011_proof_1.pdf

[10] http://en.wikipedia.org/wiki/Photosynthesis

forms of renewable energy, as indicated in Table 12-1 below[11]. This table reflects a range of examples and plants around the world and results may vary with location and scale.

Table 12-1 Estimated CO_2 emissions from different forms of electricity generation

Technology	Capacity/configuration/fuel	Estimated gCO_2e/kWh
Wind	2.5 MW, offshore	9
Hydroelectric	3.1 MW, reservoir	10
Wind	1.5 MW, onshore	10
Biogas	Anaerobic digestion	11
Hydroelectric	300MW, run of river	13
Solar thermal	80 MW, parabolic trough	13
Biomass	Forestry wood, co-combustion with hard coal	14
Biomass	Forestry wood and steam turbine	22
Biomass	Short rotation forestry, co-combustion with hard coal	23
Biomass	Forestry wood , reciprocating engine	27
Biomass	Waste wood, steam turbine	31
Solar PV	Polycrystalline silicon	32
Biomass	Short rotation forestry, steam turbine	35
Geothermal	80MW, hot dry rock	38
Biomass	Short rotation forestry, reciprocating engine	41
Nuclear	Various reactor types	66
Natural gas	Various combined cycle turbines	443
Fuel cell	Hydrogen from gas reforming	664
Diesel	Various generator and turbine types	778
Heavy oil	Various generator and turbine types	778
Coal	Various generator types with scrubbing	960
Coal	Various generator types without scrubbing	1,050

Greenhouse gas mitigation through the use of biofuels is closely linked to the source of feed for the biofuel. Australian examples for first generation fuels have been assessed[12,13] and it was found that:

- Ethanol in a 10% blend with petrol (E10) provides GHG mitigation, although with considerable variation in amount according to the source of sugar for the ethanol fermentation (molasses with and without sugar mill cogeneration, sorghum or wheat, waste starch)
- Biodiesel also offered GHG reductions, which also varied significantly according to feedstock (e.g. canola, tallow, waste oil)

Indirect land use change may have a significant effect on results for biodiesel. A notable example was the use of tallow for biodiesel manufacture and the potential for increased production of palm oil to provide feedstock for the industries that would have otherwise used that tallow. If such a broad

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[11] Sovacool BK. Valuing the greenhouse gas emissions from nuclear power: a critical survey. Energy Policy 36 (2008) 2940 - 2953

[12] Appropriateness of a 350 million litre biofuels target, by CSIRO, ABARE & BTRE. December 2003. ISBN 0 642 72244 7

[13] Life Cycle Assessment of Environmental Outcomes and Greenhouse Gas Emissions from Biofuels Production in Western Australia. CSIRO Report KN29A/WA/F2.9 to the WA Department of Agriculture and Food, September 2008

boundary is used, then the GHG aspects of palm oil production may be said to influence the use of tallow as a feedstock. Land use change is also discussed below.

Advanced generation biofuels, using lignocellulosic biomass as feedstock, are expected to offer greater GHG reductions than many first generation biofuels. For example, Herr et al[14] show the GHG benefits possible via the use of crop stubble as feed, Wu et al[15] show the relative energy returns from sustainably grown mallee trees over annual crops and Hsu et al[16] indicate the relative benefits of using wastes from sustainable forestry operations.

12.4.1 Land use change

When biomass is grown specifically for the production of bioenergy, the issue of land use change can be a significant aspect of the overall GHG emissions from that bioenergy. A report released in 2009 by the UK Environment Agency states that:

"There is increasing awareness that the impacts of direct and indirect land use change on GHG emissions should be taken into account when evaluating the GHG balance of bioenergy schemes. Direct land use change occurs when land is converted from one use to another (for example fallow land or grassland used to grow a crop). Indirect land use change occurs when an energy crop is grown on existing crop land, but land use change occurs elsewhere to allow production of the crop which has been displaced by the energy crop.

To date, most of the discussion and analysis of this issue has been in relation to the production of liquid biofuels, but the arguments also apply to biomass schemes for heat and power. On land which has been undisturbed for many years, such as permanent grassland, soil carbon levels are higher than on land which is regularly tilled. On land which has been cultivated but is then left undisturbed, such as fallow land, or land in permanent set aside, soil carbon levels gradually increase for a number of years before reaching a new equilibrium level. If such land is then disturbed by ploughing, some of this soil carbon is lost as an emission of CO_2." [17]

One form of bioenergy that has received significant attention in recent years is the use of palm oil to make biodiesel. A report published by RIRDC in 2009 examines sustainability frameworks and assessment systems. It summarises land use change in parts of Asia due to growing demand for palm oil:

"Established palm oil plantations supply markets for food and cosmetics. As the demand for palm oil increased (driven largely by biofuel markets in Europe but potentially also from an increase in demand from the food market), rainforest was cleared to expand palm oil production. The public outcry led to the formulation of the Roundtable on Sustainable Palm Oil (RSPO) guidelines. The result is that those palm oil plantations which were already existing to supply the food market can comply with the sustainability requirements of RSPO. They now supply the markets which require 'sustainably produced palm oil', while the newly cleared plantations now supply those markets which appear less discerning of the sustainability credentials and the loss of non-market values of the cleared rainforest.

This is essentially a displacement of the clearing effect from one market to another – the material consequence (rainforest clearing for new palm plantations) is therefore not tractably addressed if only one market segment (biodiesel) demands sustainability certification while another (food and cosmetics) does not." [18]

In Australia, government legislation ensures that new commercial land uses (including bioenergy) do not impact on protected native forests. Nevertheless the land use changes seen in the Asian palm oil

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14 Harvesting stubble for energy in Australia – Take it or leave it? Herr et al, Report to GRDC. GRDC Project Code: CSA00012

15 Production of Mallee Biomass in Western Australia: Energy Balance Analysis. Wu et al, Energy & Fuels 2008, 22, 190–198

16 Life Cycle Environmental Impacts of Selected U.S. Ethanol Production and Use Pathways in 2022. Hsu et al, Environ. Sci. Technol. 2010, 44, 5289–5297

17 Minimising greenhouse gas emissions from bioenergy generation. Environment Agency UK, 2009 www.environment-agency.gov.uk

18 O'Connell D et al. Sustainable Production of Bioenergy. RIRDC Publication No. 09-167, November 2009

industry highlight the importance of including land use change in lifecycle assessments (LCAs), to determine whether or not its impact is positive or negative and quantitatively significant in the overall LCA.

In a recent report for IEA Bioenergy[19], Berndes et al have also noted the complexity of land use change. Unlike the situation for palm oil described above, Berndes et al believe that some forms of biomass may offer neutral or even positive outcomes and state that:

"Bioenergy projects can lead to both direct and indirect land use change. The effects of indirect land use change are especially difficult to quantify and achieving a consensus on the extent of the impact is unlikely in the near future. Even so, it can be concluded that land use change can affect greenhouse gas balances in several ways, with both beneficial and undesirable consequences from bioenergy's contribution to climate change mitigation. However, bioenergy does not always entail land use change. The use of post-consumer organic residues and by-products from the agricultural and forest industries does not cause land use change if these materials are wastes, i.e. not utilised for alternative purposes.

Food, fibre and bioenergy crops can be grown in integrated production systems, mitigating displacement effects and improving the productive use of land. Lignocellulosic feedstocks for bioenergy can decrease the pressure on prime cropping land. The targeting of marginal and degraded lands can mitigate land use change associated with bioenergy expansion and also enhance carbon sequestration in soils and biomass. Stimulation of increased productivity in all forms of land use reduces the land use change pressure."

Agricultural wastes and integrated production systems offer considerable scope for increased bioenergy production in Australia:

- The by-products from agricultural industries already offer significant sources of biomass. Sugar cane bagasse is used in a number of commercial plants as fuel for large scale production of electricity and heat. Straw is already used overseas in commercial electricity generation and large scale demonstrations of biofuel production, however it is not yet used commercially for bioenergy production in Australia. Estimates of straw production in Australia suggest yields of almost 30 million tonne per year even after allowance for on farm sustainability, although national production may vary significantly from year to year[20].
- The theoretical potential for production of biomass alongside grain and livestock in integrated farming systems is also significant. It has been estimated that mallee eucalypts grown in rows across just a small percentage of the land on wheatbelt farms nationally could theoretically provide a total of almost 40 MT per year of dry biomass[21].

Both of these sources of biomass offer large scale opportunities for bioenergy in Australia even if only a small fraction of their theoretical potential is utilised. Importantly, both may be integrated into existing agricultural activities to minimise adverse effects of land use change and maximise positive impacts.

12.5 Food versus fuel

12.5.1 Recent experience

Most of the ethanol and biodiesel produced globally at present is made from sugar, grains, corn and oilseed crops that could also be used for food production. At times (particularly in 2008) the popular media has linked the increasing production of these first generation fuels to the concurrent increases in food prices around the world. In contrast to this view, organisations such as the US Department of

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[19] Berndes G et al. Bioenergy, Land Use Change and Climate Change Mitigation. IEA Bioenergy, 2010

[20] Dunlop M et al. Assessing the availability of crop stubble as a potential biofuel resource. Proceedings of the 14th Agronomy Conference, September 2008. http://www.regional.org.au/au/asa/2008/concurrent/emerging-opportunities/5842_dunlopm.htm

[21] Bartle J et al. Scale of biomass production from new woody crops in dryland agriculture in Australia. Int. J. Global Energy Issues. Vol. 27 No.2, 2007

Energy[22], the United Nations Environment Programme[23] and others[24] have stated that, while renewable fuel production is a contributing factor to food cost increases, so are:

- Higher fuel and input prices
- Increased demand
- Adverse climatic conditions, particularly drought
- Export food restrictions

The US government has reported that the impact of rapid growth in US ethanol production contributed 3% to the increase in world food prices during 2007/08[25] and that without such ethanol production the cost of petrol in the USA may have increased by as much as 9 cents/litre[22]. Other work has suggested that while ethanol had a cost impact on US corn prices in 2008, this was considerably reduced (generally to below 1%) by the time it reached consumers in retail products[26].

Production of first generation biofuels in Australia is at a much smaller scale than in the United States, and there is no evidence to suggest that biofuels in Australia have contributed to higher feedstock prices. Indeed the reverse appears to be the case, with grain price increases in Australia contributing to the cancellation of proposed grain-to-ethanol projects. Similarly, price increases for biodiesel feedstocks have contributed to the difficulties and reduced production in Australia's fledgling biodiesel industry.

12.5.2 Expanded bioenergy production

There is concern that increased production of biofuels in future will create greater negative impacts on food production than have occurred to date. The United Nations Environment Programme (UNEP) notes that this can be a complex and contentious issue, requiring solid planning and safeguards[23]. The UNEP suggests that a positive future view is possible, stating that: "While much has been said about the risks, little has been said about the opportunities which biofuels can bring to food security with appropriate policies and industrial commitments. Biofuels can increase food security when the necessary investment and technology improves overall agricultural productivity and subsequently food availability. While higher food prices may reduce its accessibility, biofuels can improve local economies and hence improve the ability to purchase food."

The production of biofuels in Australia could expand significantly in future, particularly as advanced generation technologies, capable of using biomass as feedstock, become commercially available. Recent experience has shown that biofuel production can interact with food production and it is important that the impacts of any proposed expansion of biofuel production in Australia are well understood and are acceptable to the agricultural sector and the broader community.

Biofuels from sugars and starches

The key criterion that would cause increased competition between production of food and first generation biofuels is the relative capacity of each industry to pay for feedstock. To date in Australia the food industry has generally been capable of paying more than the biofuels industry for feedstocks. Thus:

- grains, sugars and oilseeds are produced for consumption as food rather than for production of ethanol or biodiesel.
- low grade molasses that may be used in food production (as stock feed) is used to make ethanol.

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[22] http://energy.gov/articles/fact-sheet-gas-prices-and-oil-consumption-would-increase-without-biofuels

[23] Biofuels Vital Graphics – Powering a green economy. ISBN 978-92-807-3107-1. United Nations Environment Programme, 2011

[24] Biofuels in Australia: Some economic and policy considerations. RIRDC Publication No. 07/177

[25] Report 21 May 2008 at http://apps1.eere.energy.gov/news/news_detail.cfm/news_id=11778

[26] Babcock BA. The impact of US biofuel policies on agricultural price levels and volatility. Centre for Agricultural and Rural Devolvement, Iowa State University, June 2011

- wastes from the starch industry are used to make ethanol.
- sorghum is processed at one facility, near Dalby in Queensland, to make both ethanol and stock feed.

Biofuels from biomass

It can be seen elsewhere in this report (chapters 9, 10 and 11) that use of agricultural land to produce biomass for bioenergy must take into account the opportunity cost of that land for food production. Farmers are only expected to produce biomass for bioenergy if it is financially more attractive than producing food. The inference from the evaluation of grass production costs is that it is not a financially viable source of biomass for bioenergy. The inference from evaluation of mallee production costs is that it could be attractive for second generation biofuels at some time in the future. However this model of mallee production is based on growing mallees alongside food production, and provides environmental benefits that improve the sustainability of the overall farming enterprise.

Algal biofuels

Microalgae are generally grown in saline water so one of the main attractions of making biofuels from algae is the lack of impact on land used for food production.

12.6 Water use

The United Nations Environment Programme, Oeko Institute and IEA Bioenergy have assessed the relationship between bioenergy and water use, particularly in the context of increased bioenergy production and the potential for increase demands on finite water supplies from this and other activities in the future[27]. The report notes:

"Bioenergy strategies emphasizing high land use efficiency (i.e. maximization of bioenergy output per unit of land) to mitigate the risk of (direct and indirect) emissions from land use change may lead to a preference for high-yielding systems that receive large inputs of fertilisers, pesticides and irrigation water. Such bioenergy systems could place large demands on local water resources while increasing the pollution load from fertiliser and pesticide run-off. Thus, at some locations there may be tradeoffs to manage between climate change mitigation activities and sustainable use of water resources. Furthermore, increasing the amount of biomass dedicated to bioenergy, through the establishment of large-scale bioenergy plantations in sparsely vegetated areas, may increase evapotranspiration, leading to diversion of water from run-off to surface water as well as reduced groundwater recharge. On the other hand, if bioenergy plantations are located in such a way as to reduce run-off, reductions in soil erosion at the site, flooding, and sedimentation in rivers and dams could be achieved."

As one example of these issues, work is underway in Australia to commercialise mallee eucalypts for biomass production via narrow belts of trees that are integrated with existing grain and livestock production. With large scale potential for mallees across the wheat belt, optimisation of water use is a key element of any successful new industry. Ideally the trees will utilise excess water, protecting grain crops from water-logging, avoiding the spread of dryland salinity on farms and reducing saline water discharges into public land. Against this the trees should be planted so as to minimise direct competition for water with the crops that surround the rows of trees. See chapter 9 for more details.

12.7 Local versus global

Many sustainability issues are common to the full range of bioenergy opportunities: heat, electricity and biofuels, at different scales and using a wide range of feedstocks. However, while these are relevant issues for bioenergy globally, their assessment with respect to individual projects should always be carried out locally, using local data and with local interpretation of generic issues.

There are many examples of situations that adversely impact sustainability in one location but not in another. For example:

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[27] The Bioenergy and Water Nexus, 2011 http://www.unep.org/pdf/Water_Nexus.pdf

a) As noted above, there is concern that the expansion of palm oil plantations in parts of Asia will drive the removal of rainforest, cause GHG emissions though drainage of peatland and threaten the habitat of orang-utans and other endangered species. However in Australia there is a range of legislation to protect native forests, minimise clearing of native vegetation for any purpose and create and maintain habitats for endangered species. Potential biomass feedstocks such as mallee trees on wheatbelt farms have no adverse impacts on native forests or vegetation and actually increase biodiversity on these farms by creating habitats for animals and birds.

b) One of the core principles of the Roundtable on Sustainable Biofuels (RSB)[28] covers human and labour rights. RSB was established to provide global guidance and this principle may be relevant for some countries. In Australia, comprehensive legislation already covers such issues for all commercial activities.

c) Perennial biomass grown to create feedstock for bioenergy plants can use more water than annual crops.

    - In some situations this will create competition for water that diminishes the water available for other activities, whether they are adjacent to the biomass or some distance away and relying on surface water runoff that may be diminished through extensive tree planting.

    - In other situations, notably with careful planting of belts of mallee trees, the production of biomass can help to manage excess water that would otherwise reduce crop yields via waterlogging and cause wider damage as saline runoff.

d) The jatropha plant is capable of growing on marginal lands and produces seeds that provide oil suitable for the manufacture of biodiesel. However, while its cultivation in countries such as India is expanding, in Australia it is classified as a weed.

12.8 Legislation

Many environmental aspects of bioenergy feedstock preparation and plant operation are covered by existing legislation and procedures around Australia. For example:

- The Regional Forest Agreements in place around Australia provide for the conservation and sustainable management of Australia’s native forests.
- State and federal government legislation for production of renewable electricity includes definition of eligible biomass feedstocks.
- Environmental Impact Statements or Plans can be sought for particular bioenergy projects within well established planning frameworks.
- The construction and operation of bioenergy plants are already covered by a variety of permits and approvals needed to allow any new manufacturing facility. These may include planning approval from the relevant council, worksafe permits, approval from the local fire authority, and approvals from the EPA. A number of these processes include public display of plans and community consultations.

12.9 Standards

In June 2011, the Assistant Treasurer announced that the Australian Government would work with the Biofuels Association of Australia and the International Organisation for Standardisation (ISO) to develop internationally-agreed sustainability criteria that can be applied to industry to ensure support for biofuels does not compromise sustainable production practices and will help facilitate development and use of advanced biofuels. Australia is now one of many countries participating in the development of ISO Standard TC248 – Sustainability Criteria for Bioenergy.

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[28] http://rsb.epfl.ch

A committee draft of the new standard was released for comment in September 2012. As the full ISO process to a final standard is expected to take several more years, a parallel process is expected to occur to develop an interim biofuels standard for Australia[29]. As the ISO standard will be designed for broad applicability worldwide, an Australian standard may also help in the interpretation of the ISO standard under Australian conditions.

An ISO standard already exists for lifecycle assessments. ISO 14040:2006 describes the principles and framework for life cycle assessment (LCA) including: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements. ISO 14040:2006 covers life cycle assessment (LCA) studies and life cycle inventory (LCI) studies. It does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA.

The Waste Management Association of Australia has considered in some detail the generation of energy from waste and in 2003 it issued a Sustainability Guide for Energy from Waste (EfW) Projects and Proposals[30]. A general principle was to reduce waste and only use material with no higher net resource value.

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[29] Strategic framework for alternative transport fuels, December 2011. Dep't of Resources Energy & Tourism. ISBN 978-1-921812-86-6 (online PDF)

[30] http://www.sustainability.vic.gov.au/resources/documents/Sustainability_Guide_and_Code_of_Practice.pdf

13. Energy technologies – electricity and heat

13.1 Summary

The conversion of biomass to heat and power is well established commercially, with 90 percent of the world's modern bioenergy plants operating using combustion processes. The maturity of combustion technology is evidenced by more than 70 GW of installed bioenergy capacity globally for electricity generation[1]. Emerging thermo-chemical technologies for biomass conversion are gasification and pyrolysis.

Conventional combustion technologies create heat and can thus generate steam. This steam may then be expanded through a conventional turbo-alternator to produce electricity. A number of combustion technology variants have been developed to suit different feedstocks and plant sizes. Underfeed stokers are suitable for small-scale boilers. Grate type boilers are widely deployed. They have relatively low investment costs, low operating costs and good operation at partial loads. However, they can have higher NOx emissions and decreased efficiencies due to the requirement of excess air. Fluidised bed combustors (FBC), which use a bed of inert material such as sand, are a more recent development. Bubbling FBCs and circulating FBCs offer benefits in terms of feedstock flexibility, emissions and efficiencies.

Cogeneration is the combined production of electricity and useful heat, and improves the overall thermal efficiency of combustion plants. Co-firing of biomass with fossil fuels such as coal offers a relatively low cost bioenergy combustion pathway, in that existing fossil fuel infrastructure can be used without the need to construct new, stand-alone bioenergy plant. Co-firing can be direct, indirect or in parallel, providing flexibility for project configuration.

Gasification of biomass takes place in a restricted supply of air or oxygen and produces a fuel gas that is rich in combustible carbon monoxide and hydrogen. This gas has a lower calorific value than natural gas but can still be used as fuel for boilers, and also for engines and combustion turbines after cleaning the gas stream of tars and particulates. If gasifiers are 'air blown', atmospheric nitrogen dilutes the fuel gas to a level of 10-14 percent that of the calorific value of natural gas. Oxygen and steam blown gasifiers produce a gas with a higher calorific value. Pressurised gasifiers are under development to reduce the physical size of major equipment items, however these gasifiers are generally at the pre-commercial stage. A variety of gasification reactors have been developed over several decades. These include small scale fixed bed updraft, downdraft and cross flow gasifiers, as well as fluidised bed gasifiers for larger applications. Small scale downdraft gasifiers are noted for their relatively low tar production, but are not suitable for fuels with low ash melting point (such as straw). They also require fuel particle size and moisture content to be controlled within narrow ranges.

Pyrolysis is the term given to the thermal degradation of wood in the absence of oxygen. It enables biomass to be converted to a combination of solid char, gas and liquid (often called bio-oil). Pyrolysis technologies are generally categorised as "fast" or "slow" according to the time taken for processing the feed into pyrolysis products. Slow pyrolysis generates mainly char and gas, with very little oil. Using fast pyrolysis, bio-oil yield can be 70 percent or more of the product on a dry fuel basis. Bio-oil can act as a liquid fuel for stationary energy applications, but much development work is now focussed on upgrading the bio-oil to transportation fuel.

Anaerobic digestion is a biochemical process that usually applies to biomass feedstocks with high moisture contents. Anaerobic digestion uses microorganisms to produce a biogas rich in methane, which can be combusted for heat or used as fuel in reciprocating engines for power generation. There are numerous anaerobic digestion technologies available for different feedstocks and

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[1] Renewables 2012 Global Status Report from REN21, 2012

applications. A familiar variant of anaerobic digestion found in Australia is its use to generate landfill gas for power applications.

13.2 Introduction

Bioenergy systems can be classified into *primary* conversion technologies, which convert the biomass into heat or gaseous and liquid products, and *secondary* conversion technologies, which convert these products into the more useful forms of energy (heat and electricity). An overview of the technologies is given in Figure 13-1. Liquid biofuels are considered separately, later in this report.

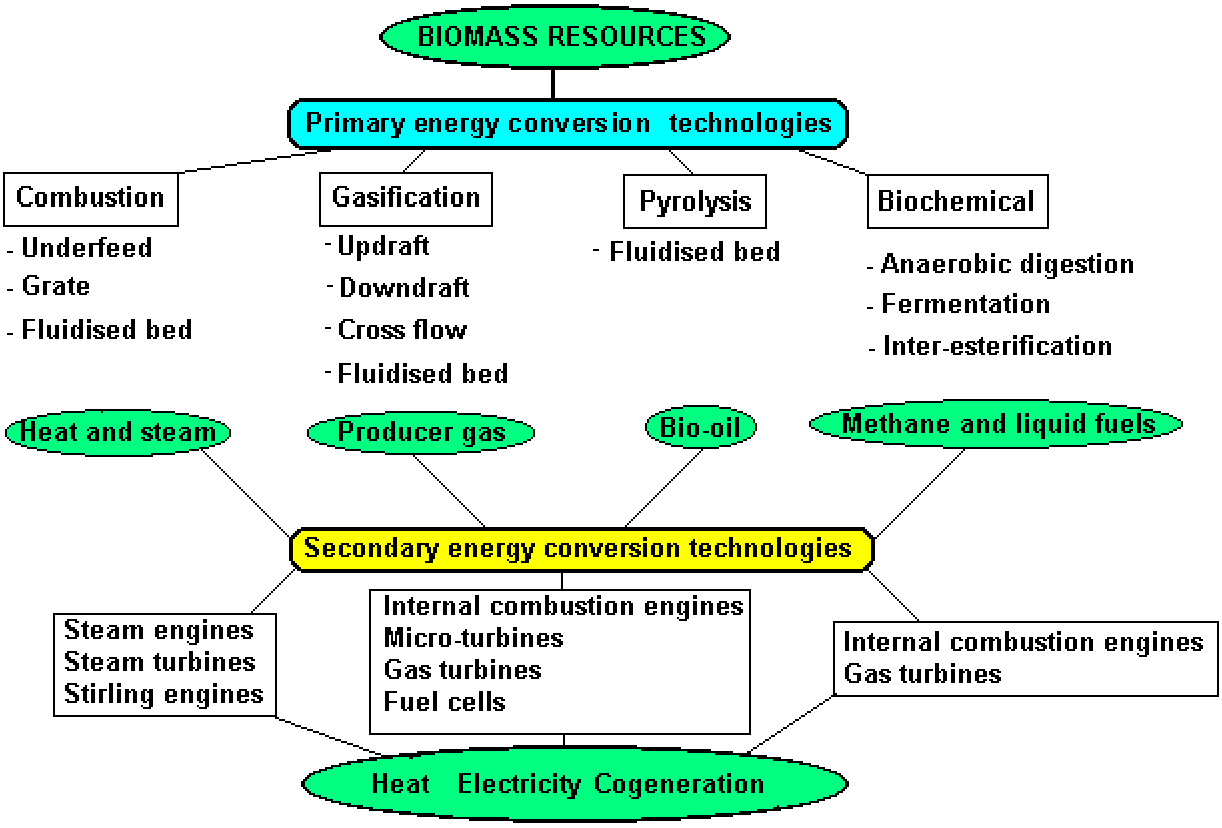


Figure 13-1: Primary and secondary conversion technologies suited to biomass projects

Bioenergy systems covered in this chapter are:

- Thermochemical energy conversion technologies: combustion, gasification and pyrolysis. This includes co-firing of biomass with fossil fuels such as coal.
- Biochemical energy conversion. Anaerobic digestion converts wet biomass to biogas, which is rich in methane and is widely used for heat, power generation.

A wide range of technologies exists to convert the energy stored in biomass to more useful forms of energy. These technologies can be classified according to the principal energy carrier produced in the conversion process. Carriers are in the form of heat, gas, liquid and/or solid products, depending on the extent to which oxygen is admitted to the thermo-chemical conversion process (usually as air). The three principal methods of thermo-chemical conversion corresponding to each of these energy carriers are combustion in excess air, gasification in reduced air, and pyrolysis in the absence of air.

13.3 Combustion

Direct combustion is the best-established and most commonly used technology for converting biomass to heat. Approximately 90 percent of the world's large-scale bioenergy plants operate through combustion processes. The USA alone has some 12,000 MW of installed bioenergy capacity, which is about the same as the total coal fired power generation capacity in New South Wales.

During combustion, biomass fuel is oxidised ("burnt") in excess air to produce heat. The first stage of combustion involves the evolution of combustible vapours from the biomass, which burn as flames. The residual material, in the form of charcoal, is burnt in a forced air supply to give more heat. The hot combustion gases are sometimes used directly for product drying, but more usually they are passed through a heat exchanger for production of hot air, hot water or steam. The combustion efficiency depends primarily on good contact between the oxygen in the air and the biomass fuel. The main products of efficient biomass combustion are carbon dioxide and water vapour, however tars, smoke and alkaline ash particles are also emitted. Minimisation of these emissions and accommodation of their possible effects are important concerns in the design of environmentally acceptable biomass combustion systems.

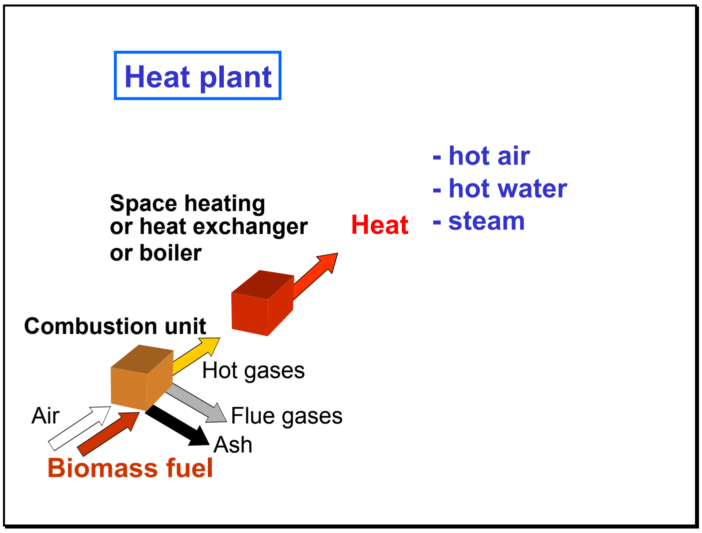


Figure 13-2 Heat plant

Biomass combustion systems, based on a range of furnace designs, can be very efficient at producing hot gases, hot air, hot water or steam, typically recovering from 65-95% of the energy contained in the fuel. Lower efficiencies are generally associated with wetter fuels. For example forest residues (left in the forest after stemwood extraction) are between 50-60% moisture content (wet basis) soon after harvest.

The most common technology for generating electricity from biomass is to use a combustion system to raise steam, and then to expand this steam in a turbine used to drive a generator to produce electricity. The process is similar to the combustion of coal in coal-fired power stations. While the production of steam using heat from the combustion of biomass is efficient, the conversion of steam to electricity (via the Rankine cycle) is much less so.

Figure 13-3 illustrates that combustion systems can range in size from the 2 kW scale for small combustion stoves to in excess of 500 MW electrical output for circulating fluidised bed systems. The smaller systems tend to have 'fixed beds' which contain the combusting biomass, while the larger systems tend to be of the fluid bed or dust firing variety.

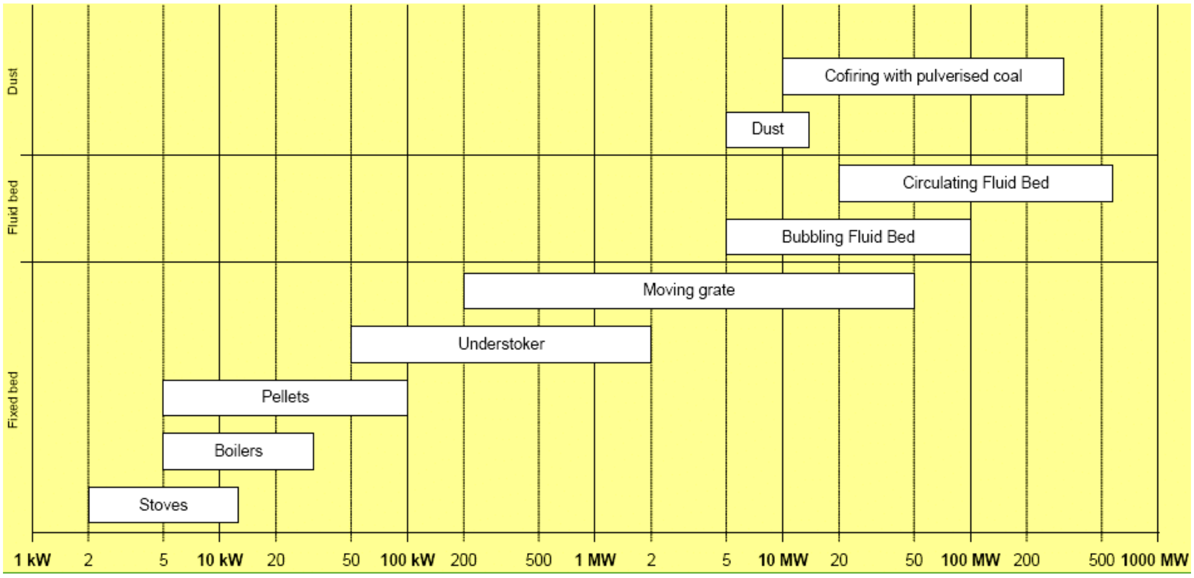


Figure 13-3 Scale of bioenergy combustion systems

The main components of a biomass power plant are shown below in Figure 13-4.

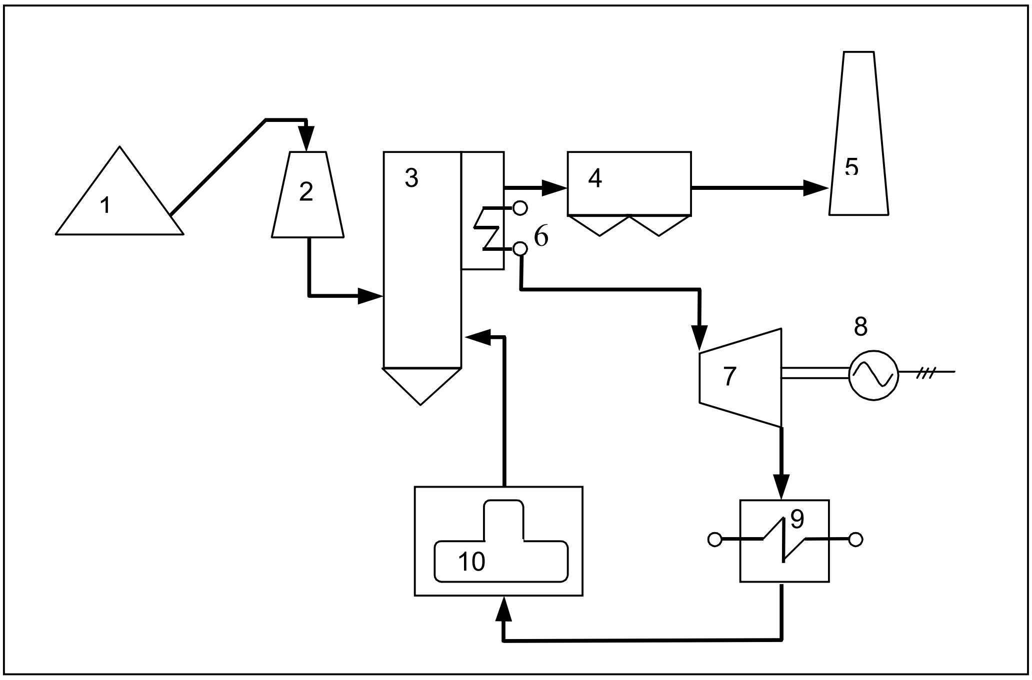
The boiler fuel is taken from the fuel storage and preparation yard (1). Fuel preparation may involve some or all of chipping, drying, sorting and blending. Fuel storage of several days to a few weeks is typical for wood fired biomass plants. The fuel is transported to a fuel feeding system (2), for example by using a large bucket on a front-end loader. In many cases the fuel feeding system consists of an intermediate silo fed by a conveyor belt, from which the fuel is fed into the furnace or fluidised bed where combustion takes place (3).

The combustion products, in the form of hot gases, are cooled down in the boiler by heating the water/steam and then exit to the flue gas cleaning systems (4), which usually consist of an electrostatic precipitator, a bag filter or a wet scrubber. The clean flue gases then pass to the stack (5). The boiler produces steam, which is superheated in the boiler superheater (6). The superheated steam enters a steam turbine (7) and drives the electric generator (8). Occasionally multiple superheaters and steam reheaters are provided to improve thermal energy conversion efficiency.

The extraction side of the steam turbine is connected to a cooling system (9) where the steam is condensed. The waste heat discharged into the cooling system is generally at a temperature that is too low for any other use. The condensate is fed into the feed water treatment system (10) and from here back into the boiler.

The overall thermodynamic efficiency of the above power generating steam cycle is determined largely by the peak temperature of the steam. The higher the steam temperature, the higher the overall power output from a given amount of biomass fuel. However, the use of higher steam temperatures and pressures requires more sophisticated and costly plant and materials (e.g. at higher temperatures and pressures, higher quality steels are needed, and boiler water purity must also be higher). Often biomass-fired steam turbine power plants operate with steam conditions that are far more modest than those in large, modern coal fired power stations. For example, the majority of 94 documented biomass plants operating in California operate with steam pressures and temperatures of about 6 MPa and 480°C, compared to 510-540°C in modern utility boilers. Biomass boilers can be built using higher steam conditions, but these are usually more appropriate for larger power plants that exhibit a favourable scale effect. There seems to be a trend towards higher steam pressures and temperatures. For example the 30 MWe Rocky Point Sugar Mill plant in Queensland has steam conditions of 7 MPa and 510°C. Biomass plant sizes in Australia are mainly limited by the economic fuel catchment area, and this leads to more modest scale biomass plants (typically less than 50 MW).

To cope with a diversity of fuel characteristics and combustion requirements, a number of combustor designs are utilised. The two main combustion systems used for biomass boilers are grate combustors and fluidised bed combustors.



1. Fuel preparation yard
2. Fuel feeding system
3. High pressure boiler
4. Flue gas cleaning
5. Stack
6. Superheater
7. Steam turbine
8. Electric generator
9. Condensing system
10. Feedwater conditioning

Figure 13-4 Main components of a biomass power plant

13.3.1 Grate combustors

With a grate firing system the biomass is fed onto a grate, on which it is carried through a drying zone, an ignition zone and a burnout zone. The grate can be either a fixed, water-cooled grate of a panel-wall type or a movable reciprocating or travelling grate with air-cooling. Systems are also available combining these features, so that the drying and ignition phases take place on a fixed grate and the burn-out takes place for instance on an attached reciprocating grate. To assure the drying and burnout of the fuel, the primary air, which is supplied under the grate, is preheated. Secondary, and sometimes tertiary air, is supplied into the furnace above the grate. The feeding systems used with grate combustors include screw feeders, spreaders and pneumatic stokers. With spreader stoker firing, the main part of the fuel will burn in the furnace in suspension. The coarser particles will not be able to burn fully in suspension and will fall down onto the burn-out grate.

(i) Underfeed stokers

Biomass is fed into the combustion zone from underneath a firing grate. These stoker designs are only suitable for small scale systems up to a nominal boiler capacity of 6MW$_{th}$ and for biomass fuels with a low ash content, such as wood chips and sawdust. High ash content fuels such as bark, straw and cereals need more efficient ash removal systems. Sintered or melted ash particles covering the upper surface of the fuel bed can cause problems in underfeed stokers due to unstable combustion conditions when the fuel and the air are breaking through the ash-covered surface.

(ii) Grate stokers

The most common type of biomass combustor is based on a grate to support a bed of fuel and to mix a controlled amount of combustion air, which often enters from beneath the grate. Biomass fuel is added at one end of the grate and is burned in a fuel bed that moves progressively down the grate, either via gravity or with mechanical assistance, to an ash removal system at the other end. In more sophisticated designs this allows the overall combustion process to be separated into its three main activities:

- initial fuel drying
- ignition and combustion of volatile constituents
- burning out of the char.

Separate control of the air conditions and the temperature for each activity are possible. Alternatively, for low ash fuels, the grate may be fixed and the fuel introduced by a spreader stoker which distributes the fuel so as to maintain an even fuel bed and provide optimum combustion conditions.

Grate stokers are available as:

- fixed grates for small scale combustion systems (typically less than 1MWth)
- reciprocating grates for larger scale
- newly developed designs that enable horizontal and vertical movement of the grate.

When the supply of primary air is controllable it is possible to operate grate firings efficiently even at partial loads down to a lower limit of 25 percent of the maximum furnace load. Some newer designs of grate systems are water-cooled to avoid slag formation and to extend the lifetime of the materials. Such attributes can increase the versatility of the combustion system, and could be considered if load or fuel requirements dictate.

Grate stokers are well proven and reliable and can tolerate wide variations in fuel quality (i.e. variations in moisture content and particle size) as well as fuels with a high ash content. Grate combustors are generally characterised by low combustion efficiency. This is caused by small, unburned particles falling through the grate and being removed with the ash, and by the poor mixing of the fuel on the grate.

Advantages of grate stoker furnaces include:

- relatively low investment costs
- low operating costs
- good operation at partial load.

Disadvantages include:

- production of NOx emissions (reduction requiring special technology and greater costs)
- excess oxygen decreasing the efficiency
- combustion conditions not as homogeneous as in other combustor types.

Figure 13-5 provides an Australian example of a 30 MW grate boiler operating at the Condong Sugar Mill on the NSW north coast. The fuel is mainly bagasse with supplementary wood waste.

Figure 13-5 30 M cogeneration plant at Condong Sugar Mill

Figure 13-6 shows a thermal application of biomass using a grate boiler at Bega Cheese, Bega, NSW where wood waste (stored in foreground) is used to provide process heat at the cheese factory. The boiler capacity is 12 MW of thermal energy.

Figure 13-6 Grate boiler facility at Bega, NSW

13.3.2 Fluidised bed combustors

In a fluidised bed combustor the fuel is burned in a bed of inert material (such as sand) distributed over a grid plate through which the combustion air is supplied. The combustion air also fluidises the bed so that it acts as boiling liquid. The biomass fuel may be introduced into the bed by gravity, screw feeder or pneumatically, and is mixed almost immediately with the hot inert material of the fluid bed. The amount of fuel in the bed at any moment is usually below 5 percent of the overall bed.

There are two types of fluidised bed combustors; bubbling (BFB) and circulating (CFB). BFB has gas fluidisation velocities around 0.5-1.5 m/s, which are too low to force bed particles to leave the combustion chamber. CFB have velocities above 3 m/s, and the bed particles leave the combustion chamber. These particles are collected in a cyclone and recirculated to the fluidised bed.

Among the fluidised bed combustion technologies, the CFB has slightly higher fuel flexibility and reported efficiency compared to the BFB[2]. CFB combustors better suit plants larger than $30MW_{th}$. The minimum plant size below which CFB and BFB technologies are not economically competitive is considered to be around $5\text{-}10MW_e$.

Fluidised beds have the ability to burn lower grade fuels and to minimise flue gas emissions compared to conventional grate combustion technologies. Fluidised bed combustors can cope with highly variable fuel properties and burn fuels with high moisture content. Wood particle size typically should have a maximum length of 150 mm, max width and thickness of 50 mm, and have side-side-side less than 100 mm for 90 percent of the material. Combustion efficiency is excellent (well above 98%) compared to grate combustors (95%). The disadvantages of fluidised bed combustors are their higher capital and maintenance costs and significant electric power demand imposed by the operation of the fans for the fluidising air.

Figure 13-7 illustrates these two types of fluidised bed combustors.

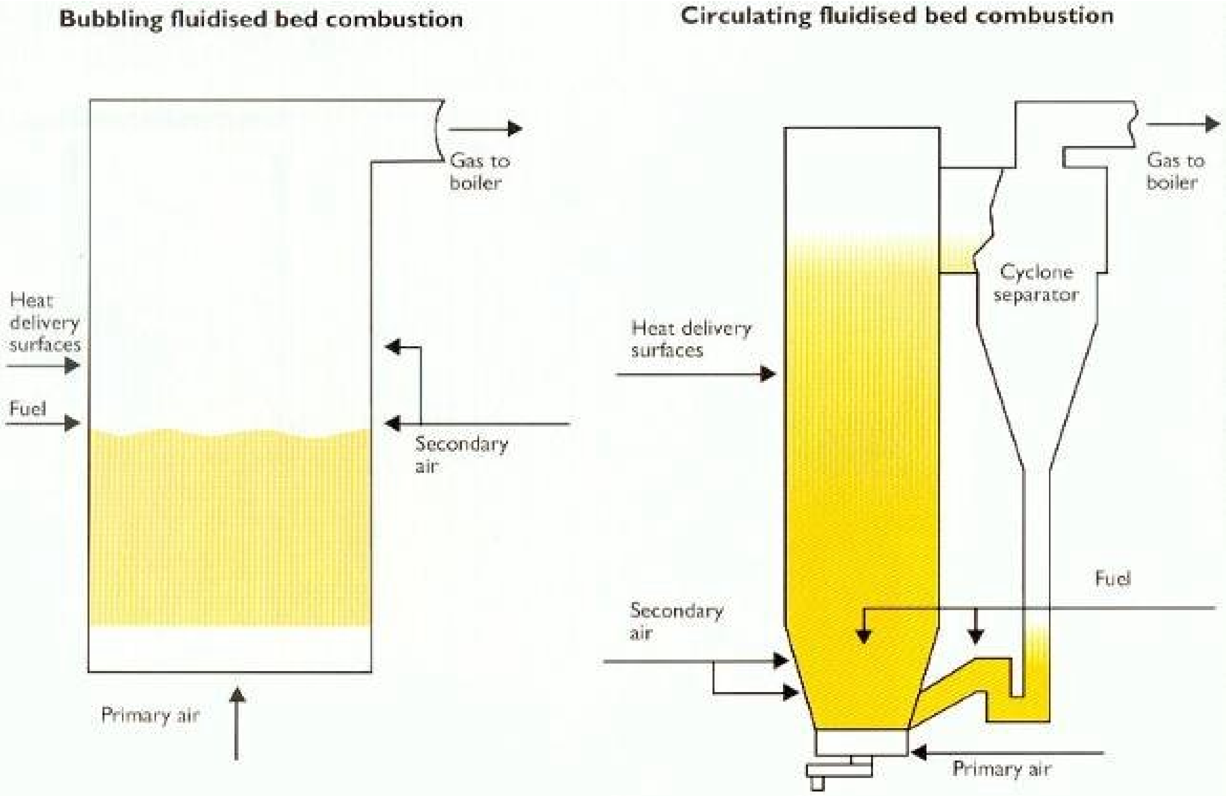


Figure 13-7 Bubbling and circulating fluidised bed combustors (Diagram TEKES)

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[2] http://www.fwc.com/publications/tech_papers/files/TP_BFB_11_01.pdf

The Cuijk FBC power plant in the Netherlands near the German border is an example of this technology. This 25 MW_e wood-chip fired plant produces steam at a temperature of 525 °C and a pressure of 10 MPa. This plant operates unattended at nights and over weekends.

One of the world's largest biomass boilers is at the Alholmens Kraft Power Plant on the west coast of Finland. The plant has a capacity of 550 MWth and an electrical capacity of 240 MWe. This sophisticated plant incorporates reheating of the steam with superheater steam conditions being 545°C and 16.5 MPa. Figure 13-8 is a cross section drawing of the Alholmens Kraft Power Plant CFBC. Its scale can be gauged from the size of the person at the lower left of the drawing. Not shown in the diagram is the extensive flue gas cleaning equipment and the stack.

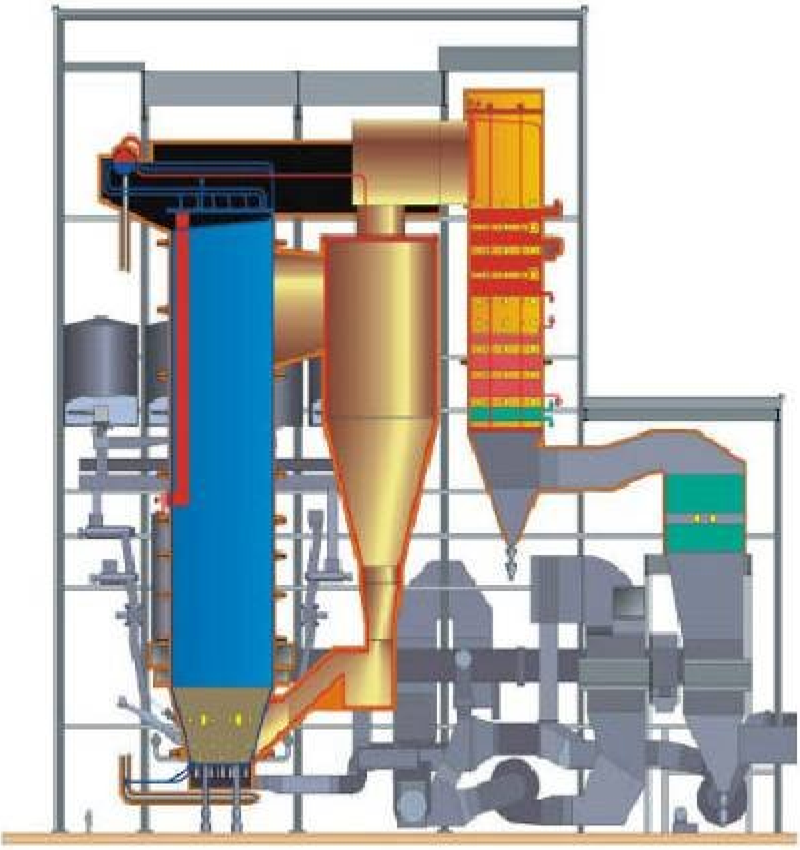

Figure 13-8 Alholmens Kraft power plant cross section (diagram Kvaerner/Metso)

13.3.3 Biomass co-firing

Co-firing of biomass with fossil fuel in existing power plants offers a path for reducing greenhouse gas emissions at lower cost than construction and operation of a stand-alone biomass power plant. In Australia, co-firing of biomass can earn Renewable Energy Certificates under the Australian Government's Renewable Energy Target (RET) if the biomass complies with the legislated requirements.

Co-firing involves biomass being used as a proportion of the input energy to the host fossil fuel plant. For existing plants this proportion is usually maintained under ten percent so as not to adversely affect operation of the host plant[3]. However in modern power plants built with co-firing in mind the proportion of biomass in the feed can be much higher. Co-firing is usually done with coal as the fossil fuel, and over 200 power plants operate in this mode world-wide. The fuel preparation requirements,

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[3] Facilitating the adoption of biomass co-firing for power generation. G. McEvilly et al. August 2011. RIRDC publication no. 11-068

combustion issues such as corrosion and fouling of boiler tubes, and characteristics of residual ash dictate the co-firing configuration appropriate for a particular plant and biomass. Co-firing can be direct, indirect or parallel firing.

(i) Direct co-firing

With direct co-firing the biomass fuel and the primary fuel (generally coal) are blended together and enter the furnace of the boiler together. This is the most common form of biomass co-firing, being the simplest and lowest cost option. Occasionally a separate biomass burner is added to the coal-fired power station furnace to cater for the different characteristics of the biomass fuel. For instance at the Gelderland Power Station in The Netherlands, wood waste is pulverised separately and directly co-fired in the pulverised coal furnace using a separate burner.

The advantages of direct co-firing are low investment cost and simplicity. The typical capital cost for direct co-firing may be as little as one tenth that of a dedicated bioenergy plant of the same capacity. A disadvantage of direct co-firing is that the biomass ash is mixed with the coal ash. Biomass ash and coal ash have different properties and co-firing may complicate possible sale and use of the combined ash that is produced.

(ii) Indirect co-firing

The combustion characteristics of biomass can be very different to coal. This particularly applies to agricultural residues and contaminated wood. One way to partially segregate the biomass fuel rather than risk damage to the larger power station boiler is to separately gasify or liquefy the biomass and then feed the product gas or bio-oil into the boiler furnace. In effect the biomass is pre-conditioned to remove problematic constituents. This cautious approach has led a number of plants to adopt such indirect co-firing.

An example of this is at the AMER Centraal Unit 9 power plant, Geertruidenberg in the Netherlands where biomass is gasified, and the gas cooled and cleaned before it enters the main coal furnace, where it supplies 85 MW_{th} of energy.

Another example or indirect co-firing was a trial conducted at the Manitowoc Power Station in Wisconsin, USA where pyrolysis bio-oil was injected above the grate of a 20 MW coal fired grate power plant to provide ten percent of the electrical output.

Figure 13-9 provides an Australian example of indirect co-firing at the Swanbank Power Station in Queensland, Australia. Here a bioreactor cell (in foreground) provides biogas, which is co-fired in the coal-fired power station in the background.

As indirect co-firing requires a separate bioenergy conversion plant, it can have a relatively high investment cost compared with direct co-firing.

(photo: S Schuck)

Figure 13-9 Indirect co-firing using biogas at the Swanbank Power parallel co-firing station

For parallel firing, totally separate combustion plants and boilers are used for the biomass and the coal fired power plants. The steam produced is fed into the main power plant where it is upgraded to higher temperatures and pressures, to give resulting higher energy conversion efficiencies.

This allows the use of problematic fuels with high alkali and halide contents (such as agricultural straw) and the separation of the ashes. An example of parallel firing is at the Enstedværket power station in Denmark, where a straw fired power plant provides 40 MW_e of the total 670 MW_e output.

Parallel firing requires relatively very high investment costs, with savings over a dedicated bioenergy plant being obtained from the dual use of the coal fired power station's turbo-alternator and steam circuit.

(iii) Multifuel operation

A recent trend in some parts of the world is to use multifuel combustion energy plants, including use of biomass fuels. A prime example is the Avedore 2 Combined Heat and Power (CHP) plant located just outside of Copenhagen (Figure 13-10)

It is has a multifuel capability, using both solid biofuels and natural gas. The biomass fuel consists of straw bales and pellets, which are mostly wood-based. On a yearly basis Avedore 2 consumes approximately 150,000 tonnes of straw and 300,000 tonnes of wood pellets. The pellets are imported to the plant, including from a pellet mill in Køge across the bay outside Copenhagen. These pellets are transported from the pellet plant to the CHP plant by barges. The output of the CHP plant is 570 MW_e and 570 MW_{th}.

(photo: S Schuck)

Figure 13-10 Avedore 2 CHP plant using both straw and wood pellets

13.3.4 Economic assessment

Technologies for using the heat of combustion to raise steam have been available commercially for many decades and can generally be regarded as robust and well proven. Electricity production with conventional steam technologies of either steam engines or turbines have overall energy efficiencies starting at as low as 5 percent (typically for small systems) and often being 20-25%. These figures are typically less that those achieved in large coal-fired power stations, generally because the latter can achieve better steam conditions than the smaller biomass plants.

Where there is a genuine demand for electricity and heat, overall co-generation (combined production of heat and power) system efficiencies can be much higher, at around 50 to 80 percent. Cogeneration is illustrated below.

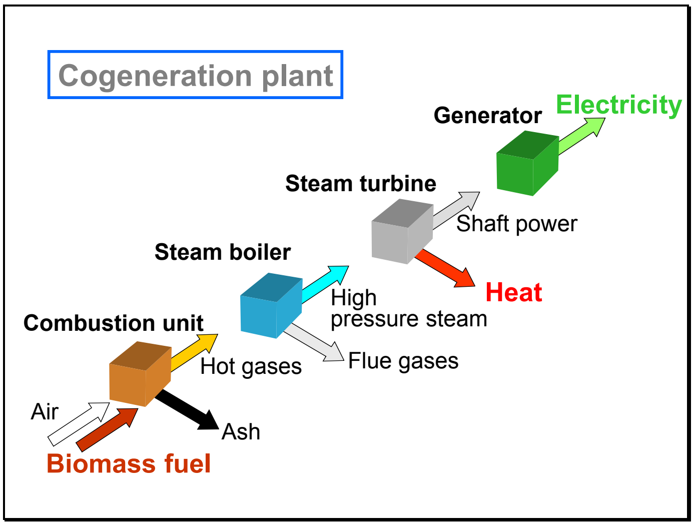

Figure 13-11 Cogeneration plant

Where biomass residues are available at low or zero cost, electricity and co-generation plants using steam technology may be competitive with electricity produced from fossil fuels. Where the biomass has to be purchased to cover costs of supply or opportunity costs, electricity prices will probably not be competitive without some form of subsidy or mandated market, such as the RET set up by the Australian Government. Biomass to electricity schemes may have particular reasons for their existence such as environmental or other benefits. Where such reasons exist, electricity price structures should recognise this. Where supportive price structures exist, steam technology will continue to be a viable proposition for biomass to electricity plants.

To improve the cost effectiveness of electricity generation from biomass, conversion efficiencies need to increase, capital costs must fall, and transport and processing capacities (such as truck payloads) need to be maximised. Raising conversion efficiencies will also increase the displacement of fossil fuels, hence maximising environmental benefits.

However, there is little scope for achieving significant efficiency improvements with steam technology over the next few years, because the technology is already relatively mature. The main technical problems with combustion technology that could benefit from further R&D concern the reactions taking place in the flue gas that cause corrosion and fouling in furnaces and boilers (especially when K, S and Cl rich biomass fuels such as straw, cereals and vegetative grasses are used). Ash melting behaviour and the variables that influence it also need further evaluation, particularly to allow better utilisation of biomass fuels that are relatively cheap but difficult to manage because of their composition and propensity to cause fouling or slagging in the bioenergy plant.

13.4 Gasification

The gasification of biomass takes place in a restricted supply of air or oxygen at temperatures up to 1200–1300°C. The basic gasification process comprises three distinct stages:

1. ***Devolatilisation***: methane and larger hydrocarbons are driven off the biomass as volatile gases by the action of heat, to leave a reactive char
2. ***Combustion:*** the volatile gases and some of the char are partially burnt in air or oxygen to generate heat and carbon dioxide
3. ***Reduction***: the carbon dioxide absorbs heat and reacts with the remaining char to produce carbon monoxide fuel gas. Due to the presence of water vapour in the gasifier, hydrogen is produced as a secondary component of the fuel gas.

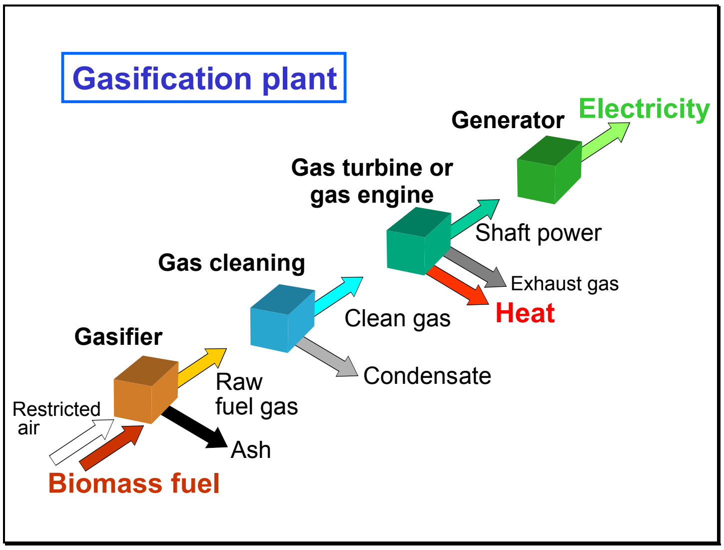

Figure 13-12 Gasification plant

This fuel gas may then be burnt to generate heat; alternatively it may be processed so that it may be used as fuel for gas-fired engines to drive generators.

Gas composition is affected by the moisture content and particle size of the biomass fuel. Overall, the products are mostly gases of low to medium calorific values. There are also small amounts of unwanted by-products such as char particles, tars, oils and ash, which tend to be damaging to engines and which must therefore first be removed or processed into additional fuel gas. This can mean that gasifier system operation is significantly more demanding than the operation of biomass combustion systems. Depending on the gasification system it can also mean that the biomass fuel must be of a consistent quality compared with combustion systems, which are often more forgiving. Note that there are exceptions to this general rule.

The final fuel gas consists principally of carbon monoxide (CO), hydrogen (H_2) and methane (CH_4) with small amounts of higher hydrocarbons such as ethene (or ethylene, C_2H_4) and ethane (C_2H_6). When air is used to drive the gasification process, the combustible gases produced are diluted with carbon dioxide and nitrogen, which have no energy value. For this reason the calorific value of the final fuel gas mixture, also known as producer gas, is typically 4-6 MJ/Nm^3. (This is the energy in an uncompressed or “normal” cubic metre of the gas.) This is only 10-14% of the calorific value of natural gas, for which commercial gas engines and gas turbines have been designed. The low calorific value makes the fuel gas less than ideal for these uses in gas engines. While a number of large scale trials have been conducted over the past two decades, there is no commercial use of wood-derived gas in turbines at present.

A large number of variables affect gasifier design, two important ones being the medium (air or oxygen) and the operating pressure.

a) Gasifiers which use air as the gasification medium (directly heated gasifiers) use the exothermic reaction between oxygen in the air and the organic materials in the fuel to provide the heat necessary to devolatilise the biomass and convert it to residual carbon-rich chars. The heat to drive the process is generated within the gasifier.

When pure oxygen is used as the medium instead of air no inert nitrogen is present and the calorific value of the gas (known as syngas) is increased to 10-15MJ/Nm3. This enables engines or turbines to be used to generate electricity with less modification. However the cost of producing oxygen and the potential hazards associated with its use have generally made oxygen blown gasifiers unattractive, especially at smaller sizes. In addition biomass already contains an oxygen component that is not present in fossil fuels, so therefore it benefits less from oxygen addition.

Indirectly heated gasifiers accomplish heating of the biomass and its gasification through heat transfer from a hot solid through a heat transfer surface. Since air is not introduced into the gasifier, no nitrogen is present as a diluent and a gas of higher calorific value is produced.

b) A pressurised gasifier will produce gas at a pressure that is suitable for direct use in gas engines or turbines and provide higher overall process efficiency. To take full advantage of operating at pressure however, a number of ancillary systems must be developed. Reliable, high-pressure feed systems have not been commercially proven and hot gas clean-up systems are required (to remove from the gas stream any contaminants that would adversely affect turbine or engine operation). Alternatively, gasifiers can be operated at low pressure and the cleaned product gas can be compressed to the pressure required for use in a gas turbine. Pressurised gasifiers are smaller than atmospheric gasifiers for the same output, but they can be more expensive to manufacture.

For fuel to be provided to a pressurised gasifier, that fuel needs to be brought from atmospheric pressure up to the operating pressure of the gasifier, before it can be introduced to the vessel. The fuel feeding system of a pressurised gasifier is thus complicated by the need for pressure seals, and the fuel feed system would need purging with inert gas to prevent explosions. These factors increase both the capital and operating costs of such a system. Some research on small, pressurised downdraft gasifiers has been undertaken but it does not currently appear to be a commercial proposition.

Cleaning the fuel gas produced can be difficult for all designs of gasifier, particularly at the small scale. If either the type of biomass fuel used, or the gasification process itself, leads to the production of dust or ash, it may well be possible to remove all of it with a hot gas cyclone. Before use in combustion engines however, the gas may also have to be cooled to intermediate or low temperatures due to temperature limitations of the fuel control systems of the engine. Reducing the gas temperature will increase the volumetric calorific value of the gas, and it will also increase the condensation of tars, making the gas even less suitable for practical use in engines. In these circumstances a gas cleaning system will be essential, possibly comprising cyclones, filters and wet scrubbers. Wet scrubbers are particularly effective as they capture tars, which are water soluble; inert dust being ash and mineral contaminants; and they also reduce the gas temperature in a single operation. However, this produces a contaminated liquid waste stream with potential toxic and carcinogenic properties. The need for treatment of such a waste stream can add to the operating cost for a proposed plant.

A number of gasification processes use high temperatures, which may be less suitable for fuels with low ash softening and melting temperatures (such as many annual crops and their residues). In such cases a gasification (or combustion) process may need to have suitable regard for water cooling internally and the possibility of vaporised salts carrying over into heat recovery equipment and causing slagging problems.

13.4.1 Reactor design

A major variable for gasifier technology is the reactor design, and various types having been developed over many decades. Usually gasifiers are classified according to how fuel and air are fed into the gasification vessel.

Figure 13-13 shows the scale of several gasifier types and their indicative overall energy conversion efficiency to electricity.

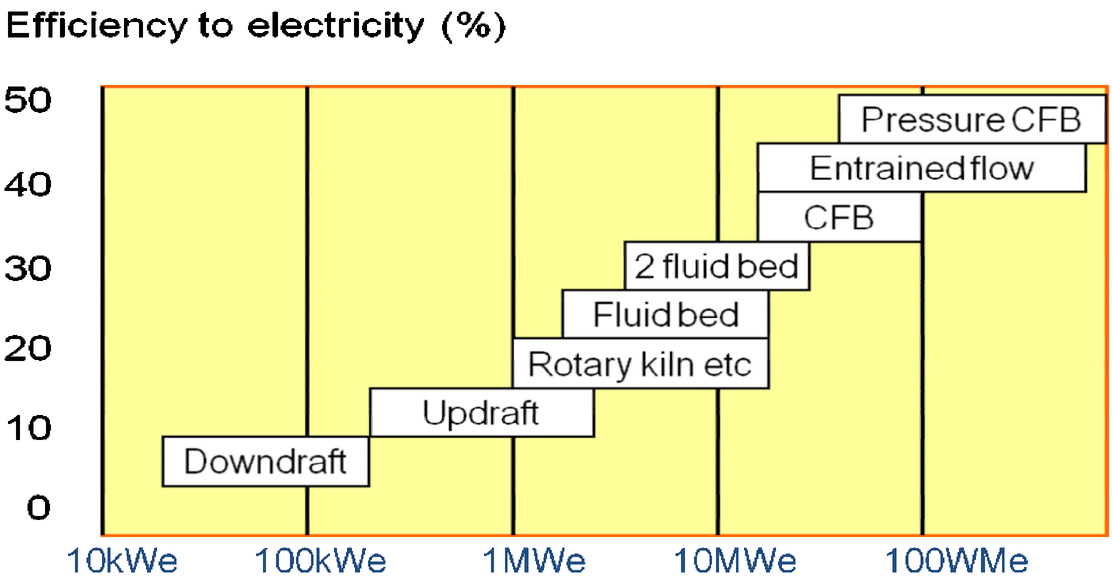

Figure 13-13 Scale of gasifier types with indicative conversion efficiencies to electricity

A number of these gasifiers are further described below and in Figure 13-15

(i) Fixed bed updraft gasifiers (counter current moving bed)

Updraft (or counter-current flow) gasifiers have combustion air blown into the reaction chamber from below while the fuel is fed in from above. An advantage of updraft gasifiers is their suitability for a large range of fuel moisture contents and particle sizes, and fuels with a low slag melting point such as straw. For heat applications up to 10MWth, updraft gasifiers are quite popular. Because the gas leaves the gasifier at relatively low temperatures, the thermal efficiency is higher than downdraft gasifiers. This type of gasifier can be used for power generation applications, but due to the high tar production the gas stream requires extensive cleaning.

(ii) Fixed bed downdraft gasifiers (co-current moving bed)

Downdraft (or co-current flow) gasifiers have the fuel fed in from the top, which then undergoes various gasification processes as it moves downwards under gravity. Air is injected either into the middle section of the gasifier or from the top and flows in the same direction as the fuel. In this design, downdraft gasifiers are not suitable for fuels with a low ash melting point, such as straw. They are popular for small-scale power generation from biomass but in order to operate properly, fuel moisture content and particle size have to be within narrow limits. In the 1980s many gasifiers of this type were installed in developing countries where the problem of unattended operation was not an issue due to cheap and abundant labour. The maximum size of this design is limited to about 1MWe. Since the 1990s several projects have been executed in Europe to improve the downdraft gasifier design. The latest research trend is the development of small scale, fully automatic units fuelled by a single, well defined biomass fuel type in order to reduce problems due to feed size and moisture content variations.

Figure 13-14 shows an Indian Ankur gasifier that has operated at the Tahune Aerial Walkway in the Huon Valley, Tasmania as part of the power supply for a visitors' centre. Combustible gases from the gasifier were fired with diesel in a generator set.

Figure 13-14 Ankur gasifier in Huon Valley, Tasmania and dual-fired diesel generator set

(iii) Fixed bed cross flow gasifiers (cross current moving bed)

These gasifiers are suitable for very small applications (smaller than or equal to 10kWe), and have been run on charcoal mainly in developing countries. Opportunities for upscaling seem to be limited. However, in 1997 a project was commenced in Europe with the objective of developing a cross flow gasifier for co-generation applications in the 0.5MWe to 2.5MWe range. The gasifier operates at high temperatures (up to 1500°C) offering the possibility of thermal tar cracking to a level satisfactory for subsequent use of the fuel gas in an internal combustion gas engine without less need for extensive gas cleaning.

(iv) Fluidised bed gasifiers

Fluidised bed technology for biomass gasification was implemented at a commercial scale in the 1980s. The major driving force that led to its development was the need for more efficient technologies at the larger scale for the utilisation of low-grade fuels such as biomass. Bubbling and circulating fluidised gasification reactors operate under much the same principles as comparable combustors.

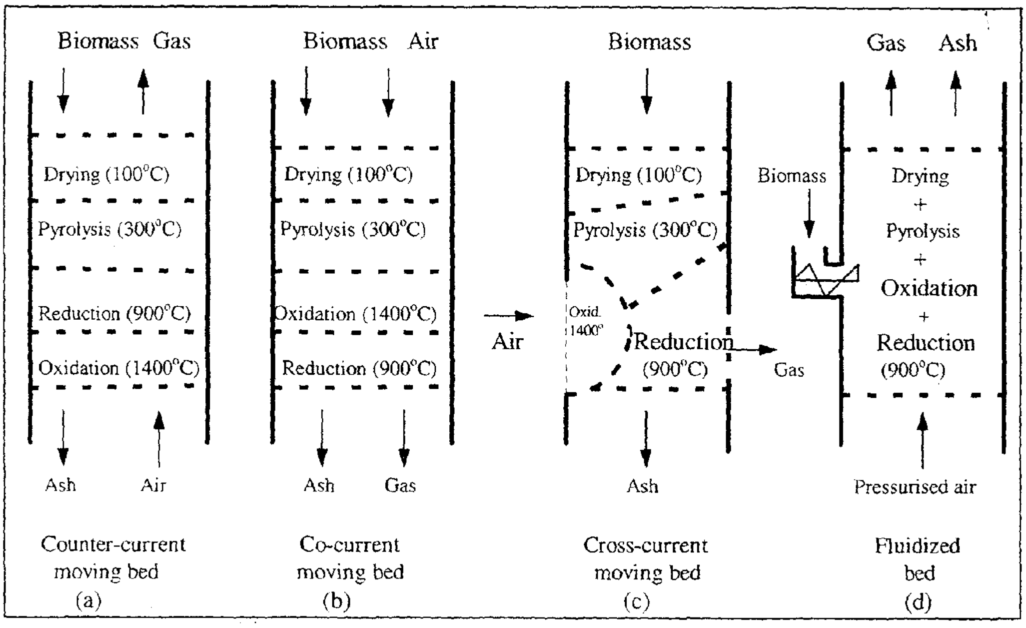

Figure 13-15 Illustrative designs of gasification reactors

13.5 Pyrolysis

During the process known as pyrolysis, biomass is heated either in the absence of air (requiring indirect heating), or by the partial combustion of some of the biomass in a restricted air or oxygen supply. This results in the thermal decomposition of the biomass to form a combination of solid char, gas, and liquid bio-oil. This is illustrated below.

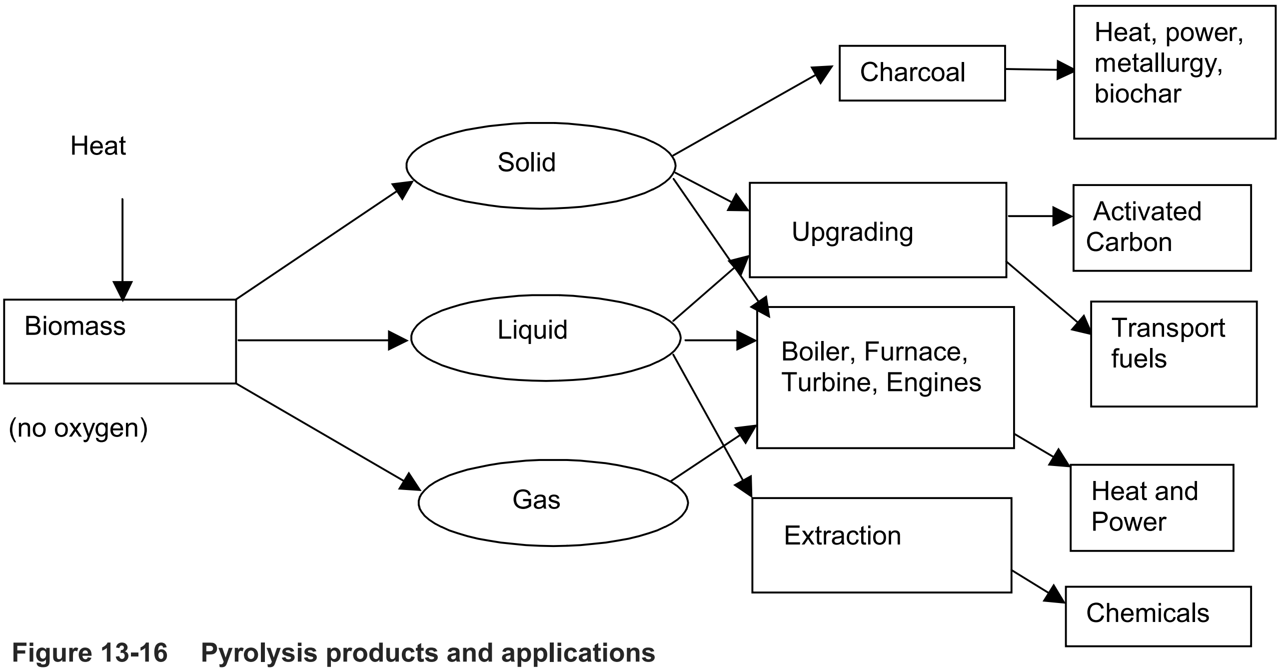

Figure 13-16 Pyrolysis products and applications

Control of the pyrolysis reaction parameters (particularly residence time, and also temperature and heating rate) provides control over the relative amounts and characteristics of the products (solid, liquid or gas) to be achieved:

- Fast (or flash) pyrolysis: high heating rates, temperature approximately 450 - 500°C and short vapour residence time (<1 second), gives high liquid yields (typically 60-70% on dry basis of the biomass) and correspondingly less char and gas production.
- Slow pyrolysis: carbonisation at temperatures around 400 - 450°C, with low heating rates and long vapour retention times gives approximately equal proportions of char, liquid and gas. Similar processes have been used for charcoal manufacture through the ages.

This is summarised as shown:

Table 13-1 Typical products of slow and fast pyrolysis

Products	Slow Pyrolysis	Fast Pyrolysis
Liquid	30-35 %	60-70 %
Gas	25-30 %	10-20 %
Solid	20-35 %	10-20 %

The equipment used to achieve slow and fast pyrolysis can vary significantly and includes rotating kilns, fluid beds and a range of other mechanisms for controlled heat transfer and effective product recovery[4].

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[4] Bridgwater A, Review of fast pyrolysis of biomass and product upgrading. Biomass and Bioenergy V38 March 2012

13.5.1 Fast pyrolysis

A major rationale for development of fast pyrolysis is the production of pyrolytic bio-oils for use as liquid fuel for stationary heat and power generation. It is possible to make bio-oil that remains quite stable for extended periods and this bio-oil could be produced at one location and transported to a heat or power plant at another location, as shown in Figure 13-17. Bio-oil has a higher energy density than solid biomass fuels such as wood chips, which offsets one of the inherent disadvantages of solid biomass; its low volumetric energy density. The higher energy density of bio-oil (16-19 MJ/kg with a density of 1,200 kg per cubic metre versus approximately 220 kg per cubic metre for wood chips) potentially allows a large reduction in the costs associated with the transportation and storage of bio-oil relative to as-harvested biomass. This may allow the expansion of the region for economic supply of the feedstock, potentially allowing greater flexibility in the location of bioenergy plants, larger scale and lower costs.

While bio-oil can be a fuel for stationary energy, with upgrading it can be transformed into a valuable and high quality transportation fuel.

A number of commercial scale fast pyrolysis plants have been built or are under construction and provide bio-oil for chemicals (generally food flavourings), heating and for upgrading to transport fuels. Further details are provided in Chapter 18 of this report. As yet there are no plants that make bio-oil specifically for power generation at separate sites.

While bio-oil is the main product of fast pyrolysis, char and combustible gases are also produced. Some or all of the gas and charcoal may be used in the plant to generate heat for the pyrolysis process. Product that is not used in this way is available for other uses or for sale. Excess gas may be used to generate additional heat or power, and char may be used in a number of applications, including:

- Bioenergy (for example via co-firing in a coal-fired power station)
- As a reductant in metallurgical industries to replace char derived from coal or petroleum coke
- As a soil additive (“biochar”)

All of these applications for char provide greenhouse gas benefits, via replacement of fossil fuels or sequestration.

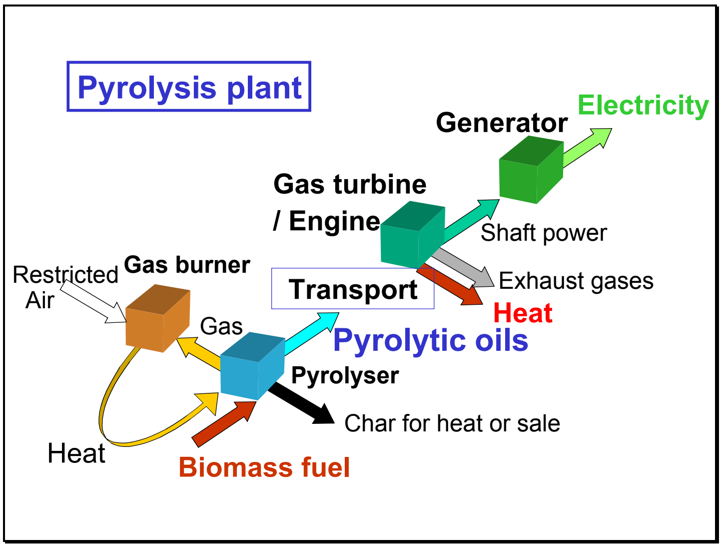

Figure 13-17 Pyrolysis plant

13.5.2 Slow pyrolysis

With increased time for the pyrolysis reaction, the mix of products can change significantly: the quantity of bio-oil declines and the quantities of char and gas increase. Char may be used as biochar or for other applications as above. Subject to suitable preparation, the gas may be used in engines connected to alternators for electricity generation.

There is considerable interest in biochar, which has been identified as a soil amendment that can simultaneously sequester carbon, and improve biomass and agricultural crop yields[5]. In Australia, the CSIRO[6], the NSW Department of Primary Industries[7] and others[8] are investigating its use in a number of different agricultural applications. This work is still at the development level, with the concept yet to be commercialised. A number of Australian companies are also developing technologies for slow pyrolysis for char and distributed electricity generation. For example:

- Pacific Pyrolysis has built and operated a large scale demonstration unit at its facility in Somersby NSW for some time. During 2012 it has been awarded state and federal government funding for the construction of commercial units in Melbourne, Victoria and Ballina, NSW.
- The Crucible Group has recently built a demonstration unit in NSW with funding support from the Australian Government.

Figure 13-18 Pacific Pyrolysis demonstration plant, Somersby, NSW

13.6 Anaerobic digestion

Anaerobic digestion is a biochemical process in which the actions of bacteria bring about the decomposition of organic matter in the absence of oxygen. This produces a biogas consisting of approximately 55-75% methane and 45-25% carbon dioxide plus some trace gases, depending on the waste stream and system design. Anaerobic digestion is a versatile process and can be applied to a wide variety of moist or wet biomass feedstocks including municipal solid waste, industrial waste,

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[5] http://adl.brs.gov.au/data/warehouse/biochar9abcm001/biochar9abcm00101/TR.2011.06_Biochar_v1.0.0.pdf
[6] http://www.csiro.au/science/Biochar-Overview
[7] http://www.dpi.nsw.gov.au/research/topics/biochar
[8] http://www.anzbiochar.org/index.html

livestock and food processing wastes and human sewage. The process may be ‘dry’ or ‘wet’ depending on the relative water content of the feedstock.

The liquid fraction of the “digestate” remaining after processing can potentially be used as a fertiliser and the solid fibre can be used as a soil conditioner.

A common form of anaerobic digestion occurs in landfills, where anaerobic digestion occurs over decades, and the resultant biogas (or “landfill gas”) may be collected and used as fuel in gas engines to generate power. A variant on landfills is bioreactor cells, where the biological process of breaking down the waste, and thus producing biogas, occurs more rapidly. There are many other forms of anaerobic digesters ranging from simple covered lagoons through to sophisticated engineered plants. These are considered further in sections below.

The typical composition and properties of biogas produced in digestors treating animal residues and that produced by landfills, is shown in Table 13-2. The heating value usually is dependent on the methane content and ranges from 20 - 30 MJ Nm^{-3}. Methane levels of between 45 and 80 percent are indicated; by comparison natural gas is essentially 100% methane.

Table 13-2 Biogas composition from anaerobic digestion

Compound	Digester Gas	Landfill Gas
Methane %	50 – 80	45 – 55
CO_2 %	15 – 45	30 – 45
H_2O %	5	5
NH_3 ppm	500 – 10,000	100 – 10,000
H_2S ppm	500 – 20,000	100 – 2,000
Other	Mercapatans and other odour molecules	Solvents with high vapour pressures

There is considerable merit in capturing and burning the methane in landfill gas that may otherwise be released to the atmosphere. Methane is twenty-one times more potent a greenhouse gas than carbon dioxide, so this form of bioenergy is a very effective greenhouse gas mitigation measure.

Specific anaerobic digestion systems are designed on the basis of the feed material, quality and requirements of the effluent, size of plant and digestion rates. Some systems such as anaerobic lagoons are relatively simple, requiring no stirring and with hydraulic retention times in the order of months. Other systems have been developed to provide hydraulic retention times of a few hours and provide a small size per unit output relative to lagoons. These high rate systems incorporate a number of innovations such as heating the digester to an optimal temperature, mechanical stirring or injection of influent to achieve stirring.

The anaerobic digestion process of farm and food processing feedstocks produces biogas, fibre (dried digestate) and liquor (liquid fertiliser). It is desirable that these three products all have viable markets to make the overall project financially viable. The relative proportions of these product streams are shown in Figure 13-19.

For organic industrial wastes and wastewater, anaerobic digestion offers several advantages over aerobic treatment. Anaerobic digestion (AD) produces an order of magnitude fewer solids, with the difference converted to biogas with energy value. Certain types of AD processes can also be extremely space efficient as they offer higher loading rates than are usually possible with aerobic processes.

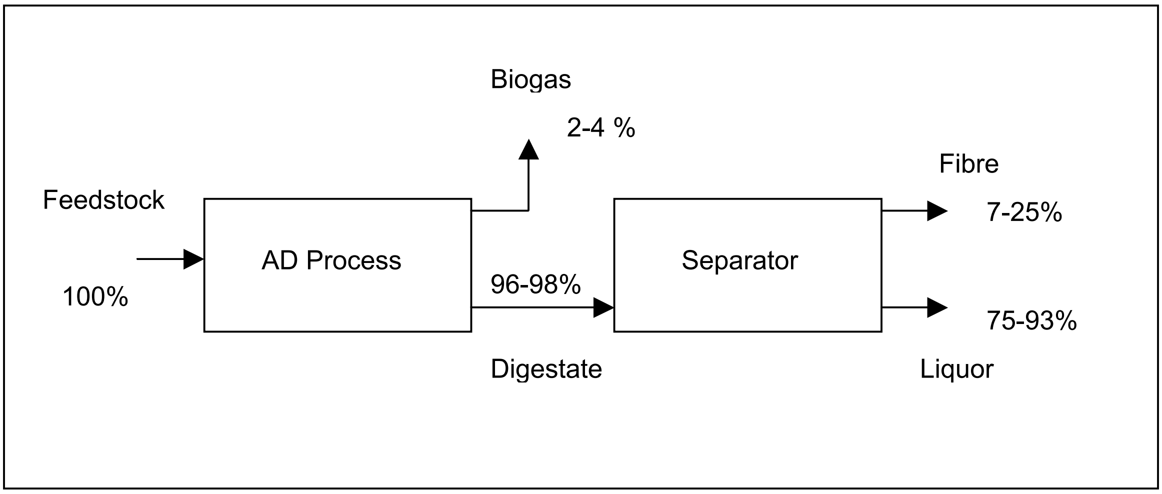

Figure 13-19 Anaerobic digestion mass balance

Anaerobic digestion and composting both offer biological routes for recycling matter and nutrients from the organic fraction of municipal solid waste. Composting is an energy-consuming process, requiring around 50-75 kWh of energy per tonne of waste input. Full-scale composting technology for MSW is in use commercially. Anaerobic digestion is a net energy-producing process, with around 75-150 kWh produced per tonne of waste input.

Methane production from anaerobic digestion generally increases with an increase in temperature, particularly when mesophilic bacterial activity is at a maximum in the range of 35-37°C. Different organisms thrive at different temperatures and above this local optimum mesophilic organisms are replaced by thermophiles, which typically achieve their maximum production of methane at 55°C. The process is only marginally exothermic and is better suited to warmer climates or when the some of the product gas is burnt to heat the process.

Biogas can sometimes be used directly as a gaseous fuel. Alternatively it may be upgraded via the removal of contaminants such as hydrogen sulphide, carbon dioxide, ammonia and water. This can be achieved by a variety of available technologies. Raw biogas is already used for heating, lighting and in engines for electrical power generation. To be used as vehicular fuel or chemical feedstock, biogas has to be upgraded and compressed and this does not currently occur commercially. Biogas plants can be operated as decentralised as well as centralised systems.

The digestate or sludge (incompletely degraded organic matter plus inorganic nutrients) remaining after the digestion process can be used as fertiliser or soil improver. The quality of this digestate as fertiliser depends on the nature and composition of the biomass digested as well as the operating conditions of the digester.

The flow chart for a generic anaerobic digester is shown in Figure 13-20 below. The quantity of biogas produced per kg (dry) of biomass digested depends on the composition of the biomass used. It has been found that substrates with a carbon to nitrogen ratio of 20:1 to 40:1 are generally desirable for AD purposes. To achieve a suitable ratio, biomass from different sources and of different compositions may have to be mixed and used together. The digestion of a mixture of biomass of different origins is called co-fermentation or co-digestion. Table 13-3 below provides some examples of biomass with their nitrogen contents and C/N ratios. In modern systems, biogas yields of 0.45 to 0.5 m^3 per kg organic matter can be expected.

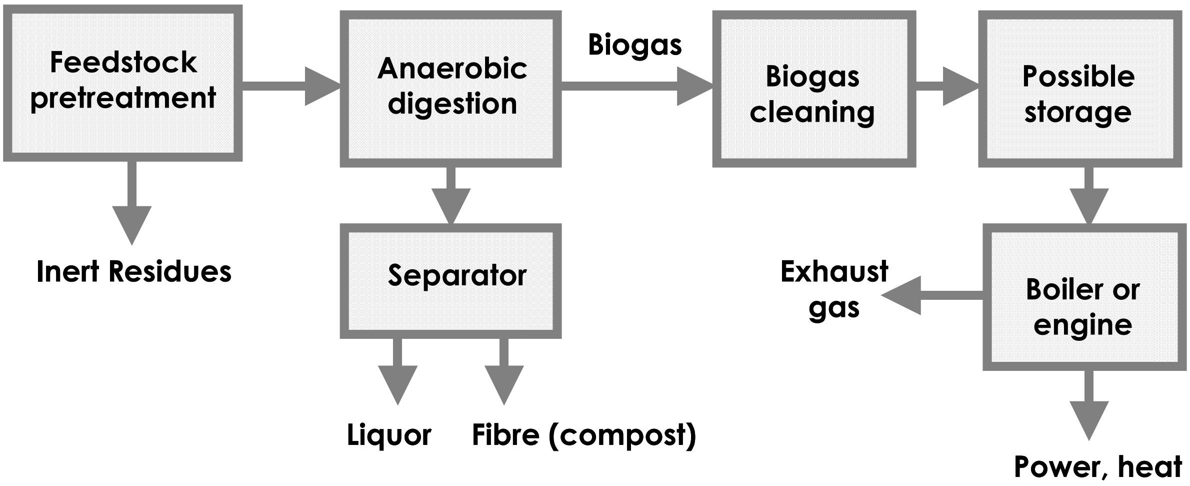

Figure 13-20 Schematic for Anaerobic Digestion

Table 13-3 Nitrogen and carbon to nitrogen ratio of various feedstocks[9]

Material	N (% of dry matter)	C/N ratio
Farm residues		
Rice straw	0.3 – 0.5	80 – 130
Wheat straw	0.3 – 0.5	80 – 130
Barley straw	0.3 – 0.4	100 – 120
Maize stalk and leaves	0.8	50 – 60
Cotton stalks	0.6	70
Sugarcane trash	0.3 – 0.4	110 – 120
Lucerne residues	2.55	19
Green weeds	2.45	13
Water hyacinth	2.38	17.6
Grass clippings	2.15	20
Livestock wastes		
Cattle manure	1.67	19
Poultry	5.0	7
Pig	3.75	5 – 10
Human habitation wastes		
Nightsoil	4.0 – 6.0	6 - 10
Urine	15 – 19	0.8
Digested sludge	5.0 – 6.0	6
Vegetable residues		
Potato tops	1.6	27
Tomato	3.3	12
Carrot (whole)	1.6	27
Fruit wastes	1.5	35
Tree wastes		
Leaves	0.5 – 1.0	40 – 80
Raw sawdust	0.25	2-8
Rotted sawdust	0.3	128

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[9] Bioenergy Options for a Cleaner Environment, in Developed and Developing Counties, R.E.H. Sims (Ed), Elsevier 2004

13.6.1 Types of biodigesters

(i) The main anaerobic technologies for organic industrial wastes and wastewater

Covered Lagoons

This is the simplest and oldest form of anaerobic digester. The retention time is measured in weeks or months. The retention time is often shortened by providing mixing to improve contact between the organic matter and the anaerobic microorganisms. The lagoon cover traps the biogas and controls odours. An Australian example of this technology is the AJ Bush plant near Bromelton, Queensland where biogas from animal rendering is digested and the biogas used for power generation. One of two covered lagoons is shown below.

Figure 13-21 Covered lagoon at AJ Bush, Bromelton, Queensland

Complete stirred tank reactors (CSTR)

CSTRs are constant volume, mechanically mixed tanks that are suitable for waste streams such as piggery and dairy effluent. They may be heated. The CSTR reactor typically has retention times measured in days, so they offer greater space efficiency than lagoon technology. However, compared to the retention times of the technologies below, they are considered to be ‘low rate’ systems.

Plug flow reactors

Plug flow reactors are constant volume, flow-through units that are commonly used with high solids manure such as is common on dairy farms. The basic plug flow reactor is a long tank, often built into the ground with an expandable cover. The retention time is commonly 15-20 days. In a plug flow reactor a new ‘plug’ of manure is added each day, pushing the older manure plugs down the tank assisted by gravity.

Anaerobic filters

This technology was commercialised in the 1980s and relies on a media substrate to retain the biomass within the reactor vessel. This material is usually made from glass, plastic or wood. These filters are usually operated in upflow mode. The hydraulic retention time is typically one day, generally making these systems more space efficient than the CSTR.

Upflow anaerobic sludge blanket (UASB)

The UASB process combines the well-mixed attributes of the contact system with internal biogas separation and clarification. Mixing within the reactor results from the gassing and influent injection occurring as new feed is distributed within the biomass bed at the bottom. The reactor contains no moving parts, but does have a baffle arrangement to separate the gas, liquid and solid phases. The gas is collected at the top of the reactor using gas collection domes. The retention time is typically well under a day. This short retention time does however work against the efficient digestion of suspended solids.

Fluidised beds
Fluidised bed anaerobic digesters further improve loading rates and reduce size and hence cost. They use a 'carrier' material such as sand so the biomass can be retained in the reactor even against very strong hydraulic flow through rates. The retention is measured in hours.

(ii) Common anaerobic digesters for municipal solid waste (MSW)

Wet single-step
Here, the MSW is slurried with a large proportion of process water to provide a dilute (10-15 percent dry solids) feedstock than can be fed into a complete mix tank digester. This technology lends itself to co-digestion with more dilute feedstocks such as animal manures and organic wastes.

Wet multi-step
The MSW is slurried with water of recycled liquor and fermented by hydrolytic and fermentative bacteria to release volatile fatty acids which are then converted to biogas in a high-rate industrial wastewater AD, usually an anaerobic filter or UASB. These digesters are suitable for food processing wastes.

Dry continuous
These batch-load a continuously fed digestion vessel with a feedstock with a dry matter content of 20-40 percent. Completely mixed and plug flow systems are available. The minimal water addition requirement allows operation at thermophilic digestion temperature (50-55°C).

Dry batch
This type of anaerobic digestor batch loads a vessel with raw feedstock and inoculates it with digestate from another reactor. During digestion leachate is recycled to maintain uniform moisture content and distribution of the methane producing bacteria in the sealed vessel. When digestion is complete and a batch is unloaded and a new batch of MSW is introduced.

Bioreactor landfills
Bioreactor landfills are similar to conventional landfills except the anaerobic digestion process is accelerated and better controlled. A bioreactor landfill usually consists of a series of lined cells with leachate recycling to speed up digestion. An example of this technology has been established near the Swanbank Power Station in southern Queensland, where bioreactor landfill gas has been co-fired in the adjacent coal fired power station.

Landfill gas
In Australia, anaerobic digestion of municipal solid waste in landfills to produce biogas has been carried out at commercial scale for over twenty-five years. It is a mature and competitive bioenergy option, with well over 40 projects currently providing approximately 140 MW of electricity from landfill gas across Australia. The largest landfill gas project in Australia is the 13 MW_e plant at Lucas Heights, NSW.

With landfill gas, a well field is bored into the landfill to extract the gas under mild suction. The gas is purified and dried before powering gas engines. As the gas producing life of a landfill decays over twenty to thirty years, it is common to provide modular generator sets to match the gas flow with generating capacity.

13.6.2 Project examples

Earthpower Technologies Sydney opened a large scale anaerobic digester in 2003 at Camellia, near Parramatta. The feedstock of this 82,000 tonne per year digester is source separated organic wastes from the domestic, commercial and industrial sectors, essentially food waste. The anaerobic digestion technology utilised in the Earthpower projects was sourced from BTA Biotechnische Abfallverwertung GmbH & Co. KG of Germany. It has been modified and adapted with local innovations. The following photo depicts one of the main digester tanks of the Camellia plant.

Figure 13-22 Earthpower Technologies - Sydney food digester

Below is an example of a concrete egg-shaped digester at the Woodman Point Waste Water Treatment Plant near Perth, WA.

Figure 13-23 One of two egg shaped anaerobic digesters at Woodman Point, WA

14. Secondary energy conversion technologies

14.1 Summary

Secondary energy conversion of biomass fuels (solid, gas or liquid) to electricity can be achieved using well-established technologies. These include internal combustion engines, steam turbines, steam engines and Organic Rankine Cycle (ORC) technologies.

Steam turbines coupled to electrical alternators convert steam energy from biomass boilers to electricity. This is a mature technology, similar to that used in coal-fired power stations worldwide. Overall energy conversion efficiencies are generally in the range 15-30 percent, depending on scale and engineering complexity. At small scale, steam turbines tend to be less efficient. Overall steam cycle efficiency is a function of steam temperatures and pressures. Operating efficiency is a trade off, with plant capital cost increasing to achieve more efficient design.

Steam engines are proven, robust technology and are mainly suited to constant speed operation in industrial environments. Steam engines are only produced in small sizes and are therefore relatively expensive per unit of electrical output.

Conversion plants based on the Organic Rankine Cycle use a high molecular weight working fluid in a closed cycle instead of water, providing modular power units sized to 2 MW_e or more.

Gasified biomass, composed mainly of carbon monoxide and hydrogen gases, can provide the fuel for internal combustion engines. Overall conversion efficiency of biomass energy to electricity is typically less than 25%, with the higher efficiencies for larger units. A key issue is removing tar and particulate matter from the gas to allow trouble free engine operation. Equipment for small-scale biomass gasification-engine projects is available commercially from companies in Europe, the USA and India.

There are many energy conversion technologies that are being investigated by research groups worldwide but have not achieved broad commercial use. These emerging technologies include Stirling engines, indirectly fired gas turbines, directly fired pressurised gas turbines, micro-turbines, advanced combined cycle gasification technologies, and fuel cells.

Stirling engines are ‘external combustion’ engines that operate through the expansion of a gas. There is no contact between the biomass generated heat and the moving parts of the Stirling engine. Stirling engines are available in small sizes up to 150 kW_e, making them suitable for distributed generation. Worldwide a number of Stirling engines have been developed, although they are yet to be commercially proven.

Indirectly fired gas turbines use a heat exchanger to reduce the requirement for cleaning gasified biomass. Several large-scale developments with indirectly fired gas turbines have occurred in recent times, mainly in Europe. With directly fired pressurised gas turbines, hot combustion gas from a pressurised gasifier is fed into a standard gas turbine.

Micro-turbines are a variant on conventional gas turbines. Most designs incorporate a recuperator to recover exhaust energy to attain overall efficiencies of 20-30 percent. Sizes are in the 25-250 kWe range. They operate at high speeds and use sophisticated electronics to generate standard alternating current electricity. Currently there are no commercially operating gasifier/micro-turbine systems. Existing microturbine systems are generally fuelled on natural gas or biogas.

Biomass Integrated Gasification Combined Cycle (BIGCC) systems achieve increased overall efficiencies by simultaneously using a gas turbine and a steam turbine. Gas cooling and recovered exhaust heat from the gas turbine are used to raise steam for the steam turbine. A number of BIGCC projects were built to demonstrate this concept some years ago, however none have remained in

operation. An example of such a project was the plant at Värnämo in Sweden, which was subsequently converted into an advanced biofuels research facility.

Fuel cells are electrochemical devices in which hydrogen-rich fuel is used to produce heat and power. They can operate at high overall energy conversion efficiencies and are now entering the market in selected applications for stationary power (although using feeds other than biomass). They can also be used in for distributed heat and power production. Fuel cells could operate using fuels derived from biomass but no such units are in general use yet.

14.2 Introduction

The primary biomass conversion stage produces heat or a modified biofuel, with energy carriers including air, gas, solids and liquids. There are several secondary energy conversion technologies for generating electricity at a range of scales, and in some cases they are also used in co-generation systems for electricity and heat. They include:

- internal combustion engines
- steam turbines
- steam engines
- Organic Ranking Cycle modules
- Stirling engines
- indirectly fired gas turbines
- directly fired pressurised gas turbines
- micro-turbines
- fuel cells
- advanced power cycle technologies.

The first four items in the list above are mature, commercially available technologies, while other items in the list are at various stages of demonstration or development. The state of technology development with respect to commercialisation is discussed here, and for each technology some project examples are provided.

14.3 Internal combustion engines

Reciprocating or internal combustion engines (ICEs) are among the most widely used prime movers to power small electricity generators. Advantages include large variations in the size range available, fast start-up, good efficiencies under partial load, reliability and established support infrastructure. Several types are commercially available but those of most significance to stationary power applications are four-cycle spark-ignition (Otto cycle) and compression-ignition (Diesel cycle) engines. The primary difference between Otto and Diesel cycles is the method of fuel combustion. The Otto cycle uses a timed spark to ignite a pre-mixed fuel-air mixture whereas the Diesel engine compresses the air introduced into the cylinder, thereby raising its temperature to the ignition temperature of the fuel, which is then injected at high pressure.

The essential mechanical parts of both engine designs are similar in that they use cylindrical combustion chambers, close fitting pistons and a crankshaft to transform linear motion into rotary motion to drive the generator. Large, modern, compression ignition engine generating sets can attain electrical efficiencies better than 30% and operate on a variety of fuels. They can provide higher partial load efficiencies than spark-ignition engines because of their leaner fuel-air ratios at reduced loads.

14.3.1 Gas from anaerobic digestion

Biogas produced in landfills and biodigesters is a suitable fuel for powering spark ignition ICEs, with its use being fairly common in wastewater treatment plants, landfills, and food processing plants.

Figure 14-1 shows the machine hall at the Carrum Downs waste water treatment plant, Victoria where biogas from the sewage treatment plant powers seven generator sets to produce up to 17 MW of electricity.

Photo: S Schuck

Figure 14-1 Carrum Downs biogas engine-generator sets

14.3.2 Syngas from biomass gasification

Gas cleaning for tar and particle removal is the key issue for successful application of syngas from biomass gasifiers in ICEs. Few of the current gas cleaning systems have demonstrated long term compliance with the gas quality requirements for satisfactory ICE application and few engine manufacturers are prepared to maintain their warranties for limited applications using biomass gasifiers. Commercial gasifier suppliers tend to recommend engines from manufacturers with which they have built up experience.

Small scale gasification and ICEs are used in hundreds of applications in India and other developing countries, often as an alternative to diesel-fired power generation. In Australia several small-scale demonstration projects have linked biomass gasifiers with ICEs. For example, Forestry Tasmania has operated a small Ankur downdraft gasifier on wood waste to dual fire a diesel generator set with producer gas. In this configuration, combustible gas, essentially carbon monoxide and hydrogen from the gasifer passes through a series of filters and introduced into the air intake of a conventional diesel engine powering a generator set. During operation, the gasified biomass can provide up to 70 percent of the fuel, the balance being diesel fuel.

14.4 Steam turbines

Steam turbines are widely used throughout the world in large-scale power generation plants. Much of Australia’s electricity already comes from such plants operating on brown and black coal feed. The steam cycle for power generation with coal or biomass as feed typically follows a closed cycle known as the Rankine cycle. Water is heated, boiled and superheated in a boiler. Some of the energy contained in the steam is converted into rotational motion by expanding it through a turbine. The turbine is connected to an electric generator. After expansion in the turbine, the steam is then passed through a condenser, where it is cooled so that it condenses into liquid, which is sent back to the boiler to complete the cycle. Where the production of electricity is to be maximised, the steam turbine may exhaust into a vacuum condenser. Figure 14-2 shows the role of a steam turbine in electricity production.

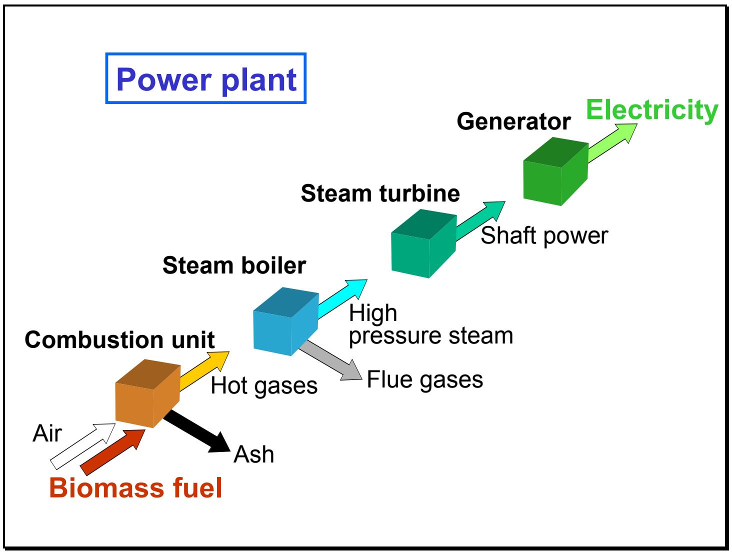

Figure 14-2 Steam turbine power plant

A steam turbine is particularly suited for large power outputs which, combined with the cost and reasonably high efficiency at this scale, is the reason for its wide use in large-scale power plants (Figure 14-3). System efficiencies can vary between 15 and more than 35% depending on the boiler and turbine design and steam parameters.

Higher efficiencies are generally found in larger plants, where more energy may be "captured" by the steam and released in the turbine. This helps make co-firing of biomass in coal-fired power plants attractive, as the biomass used in a large coal-fired power station may well provide significantly more electricity than an equivalent amount of biomass burnt in a small, dedicated bioenergy plant.

Figure 14-3 Steam turbine driving a 25 MW_e generator in a wood-fired power plant in Canada

Heat available from the steam condenser will be at low temperatures, usually below 50°C, which is insufficient for most heating applications, so this heat is normally simply released to the atmosphere or a large water course. Where there is need for heat as well as electricity, the plant can be configured to provide higher temperature steam or process heat by:

- taking some steam directly from the boiler
- extracting partially expanded steam from a turbine designed for that purpose

- arranging for the steam turbine to produce exhaust steam at the required temperature.

All three options reduce the amount of electricity available from the plant although the overall recovery of useful energy from the biomass feed may be much higher, 50-80% being possible for well designed co-generation systems.

Capital cost per unit of output for a steam turbine are much smaller for large units than for small units. At the small scale (below 2MWe), capital cost is often a significant obstacle for their uptake compared with ICEs. Steam turbines benefit from the fact that boilers and steam systems use mature technology, and the turbines themselves are also well understood and supported commercially. Disadvantages other than the high comparative investment costs can include low efficiency at the small scale, poor partial load efficiency, relative complexity for maintenance, and difficulties with poor steam quality (i.e. low pressure and high water content).

An Australian example of a 1.5 MWe steam turbine power system is at Sun Coast Gold Macadamia, Gympie, Queensland (see Figure 14-4)

Source: Stephen Schuck

Figure 14-4 1.5 MW Steam turbine at Sun Coast Gold Macadamia, Gympie

14.5 Steam engines

Steam engines are also proven technology but suited mainly for constant speed operation in industrial environments. Steam engines are only produced in small numbers, and are relatively expensive per unit in terms of $/kW. The efficiency of steam engines largely depends on the quality of the steam, which means that boilers with good steam pressures and temperatures are needed. Steam engines need steam with a pressure of at least 10 bar and a temperature of at least 180°C. Traditional steam engines are reliable and have low maintenance costs. The principle of a steam engine is similar to that of an ICE, the main difference being that in a steam engine the working fluid is steam, as opposed to fuel combustion products in an ICE. Most steam engines are double acting in that steam expands during both the forward and backward stroke of the piston. As a result a steam engine is lighter and smaller than an internal combustion engine for a given power output. Steam engines can be divided into traditional steam engines, modified steam engines, and systems which use diesel engine components thus reducing the production cost.

The main market for traditional steam engines in biomass systems would be as co-generation units in quantities which are too small for the economic operation of a steam turbine. Some small steam engines (several kW output) are already in use privately in Australia to drive small generators with battery backup in Remote Area Power Supplies. Strathsteam in South Australia is one company that has provided units for this purpose.

Advantages of a traditional steam engine include:

- it is a proven, robust technology (at least for traditional steam engine designs)
- able to withstand constant operation in an industrial environment
- has no internal corrosion of components as opposed to an internal combustion engine or gas engine
- needs steam to operate, not cleaned gas from a suitable gasifier
- can have reasonably good efficiency for small engines if well designed and when used in connection with standard industrial boilers.

Disadvantages include the low efficiency when used with steam of poor quality (usually as low pressure) and the poor image of old design and outdated technology.

Steam engines are available in different sizes ranging from a few kW to more than 1 MW_e. Specific investment costs for the steam engine alone vary significantly, with small units having a much higher cost per kW than large units. However, other than for a few applications of several kW, there are no known biomass systems operating with steam engines in Australia.

14.6 Organic Rankine Cycle plants

Organic Rankine Cycle (ORC) power plants are based on a variant of the more conventional Rankine steam cycle. Instead of water, ORC plants use high molecular weight organic fluids which are vaporised and expanded in a closed system. The ORC system generally harnesses low to moderate temperature waste heat (70 to 300°C) via hot water, low pressure steam or thermal oil. It can use exhaust heat produced when a reciprocating engine or gas turbine is in operation. An advantage in comparison to a conventional steam turbine plant is the possibility of part-load operation in the range of between 10 and 100 percent full load. ORC generators are currently available from less than 200 kW_e to more than 1 MWe and hundreds of units are operating worldwide. Examples of units with biomass feed include cogeneration units for Sky Broadcasting and Heathrow Airports in the UK[1] and a proposed multi-unit plant in Canada to generate 6.5 MW_e[2].

Gross efficiencies of 10-14 percent are reached in ORC generators of approximately 300 kWe to 1.5 MWe, at thermal oil feed temperatures of 300° C, when operated as cogeneration plants[3]. For optimised electricity generation, greater than 20 percent efficiency is possible. However, the net efficiency of the ORC plant can be considerably lower that the gross efficiency, due to the relatively high power consumption of the ORC plant.

Australian company Pacific Heat and Power installed a PureCycle® ORC power system at Gympie Timber Company in Queensland in 2011. Figure 14-5 shows this 280 kWe ORC unit. Gympie Timber uses sawmill waste heat to power this unit. In Victoria, a 70 kWe ORC unit that was manufactured by Victorian company gT Energy Technologies[4] operates at Reid Timber east of Melbourne.

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[1] http://www.pw.utc.com/media_center/press_releases/2012/05_may/05-02-2012_00001.asp

[2] http://www.kleanindustries.com/s/environmental_market_Industry_news.asp?ReportID=523874

[3] The Handbook of Biomass Combustion and Co-firing. Edited by S van Loo and J Koppejan, IEA Bioenergy Task 32, Earthscan, 2008.

[4] http://www.g-tet.com/uploadedfiles/file/gTET%20Reid%20Bros%20installation.pdf

Source: Stephen Schuck

Figure 14-5 280 kWe ORC module driven by bioenergy, Gympie Timber Company

14.7 Emerging technologies

There are several other new and emerging bioenergy conversion technologies at various stages of development and demonstration. Some of these are being developed for small scale applications, while others are being developed at a larger scale (30 MWe), with emphasis being placed on improved energy efficiency, environmental performance and lower cost.

14.7.1 Stirling engines

Stirling engines can utilise any source of heat provided that it is of sufficiently high temperature. They differ from ICEs in being external combustion engines, fuel being combusted outside the engine and the heat then transferred into the cylinder by a heat exchanger or via the cylinder wall. A working gas, enclosed by two pistons in a vessel, moves continuously back and forth between hot and cold spaces in a regenerator and is therefore continuously heated or cooled. There is no contact between the moving parts of the Stirling engine and the biomass generated heat. As a result the lifetime is relatively long and maintenance intervals are large.

In the late 19th and early 20th century several thousand Stirling engines with a maximum output of around 4kW were in operation in Europe and the USA. However the Stirling engine was later replaced by the more efficient and lighter internal combustion engine.

Stirling engines are available in the 0.5 to 150kW_e range and a number of companies are working on its further development. However, only a relatively few engines have been introduced to the market to date. Considerable R D & D work has taken place for use of Stirling engines with biomass fuels. Several prototypes have been developed over the past decade however there appear to be no units in commercial operation with biomass feed anywhere in the world.

Figure 14-6 shows a 70 kWe, four cylinder Stirling engine in Austria, which was built 2005 and has an electrical efficiency of approximately 12 percent.

Source: IEA Bioenergy Task 32 and BIOS BIOENERGIESYSTEME GmbH, Austria

Figure 14-6 70 kWe Stirling engine

14.7.2 Indirectly fired gas turbines

Gas turbines based on conventional designs but with the combustion chamber replaced by a heat exchanger are termed “indirectly-fired”. Heat produced by external combustion in a standard combustor is transferred by clean air as the working fluid through the close-coupled heat exchanger, so that the need for clean gas is less crucial. However before hot combustion gas enters the heat exchanger, some gas cleaning is still necessary. Research has been focused mainly on the heat exchange system because all other components are mass produced. At least two demonstration units have been built in Europe over the past decade however there is no ready evidence of their ongoing operation or of follow up with commercial plants.

14.7.3 Directly fired pressurised gas turbines

In this system hot combustion gas from a pressurised gasifier is lead into a directly fired pressurised gas turbine. As the gas temperature is usually higher than the maximum allowable inlet temperature of the gas turbine, it is mixed with cooler air.

The concept of a pressurised air-blown fluid bed gasifier coupled to a gas turbine of capacity 225kW$_e$ was evaluated in North Carolina. Problems experienced with this system were the biomass feed system, ineffective hot gas clean up, and a relatively low conversion efficiency. Major engineering challenges yet to be resolved are the design of a gas turbine fuel supply and combustion system that will accept and burn the hot gas. The system is yet to become commercial.

A commercial demonstration project was built in Red Boiling Springs, Tennessee USA by Bioten GP. This 5 MWe plant appeared to be operational in 2004[5] but no current information is available on the plant or the company that built it.

14.7.4 Micro-turbines

A micro-turbine is similar to a gas turbine, except that most designs incorporate a recuperator to recover part of the exhaust heat for preheating the combustion air and hence increase overall efficiency. Several competing manufacturers are developing units in the 25-250kW$_e$ range. Most manufacturers are pursuing a design where the compressor, turbine and generator are mounted on a single shaft supported on lubrication-free air bearings and operating at speeds of up to 120,000rpm.

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[5] http://www.cogentech-inc.com/sitebuildercontent/sitebuilderfiles/BioTenSummaryPackageNov04.pdf

Groups investigating gasifier /micro-turbine systems are targeting lower electricity costs than may currently be achieved by gasifier /ICE systems. To our knowledge there are currently no commercially operating gasifier/micro-turbine systems anywhere in the world.

US company Capstone is a world leader in micro-turbines. One application of its products is at a Los Angeles landfill, where 50 micro-turbines operate on landfill gas. Western Water in Victoria has installed a Capstone microturbine at its Melton plant to the west of Melbourne.

14.7.5 Advanced combined cycle gasification technologies

It has been noted elsewhere in this report that syngas from a gasifier may be used to power a gas turbine, subject to the syngas first being suitably prepared for use in the turbine. The gas turbine produces waste heat and this heat may be used to generate steam, which may be passed through a steam turbine. Both turbines may be coupled with alternators to generate electricity. Operation of two separate turbines in this way is called combined cycle power generation and if biomass is proposed as feed it is commonly referred to as biomass integrated gasification combined cycle (BIGCC or IGCC) systems. (Figure 14-7)

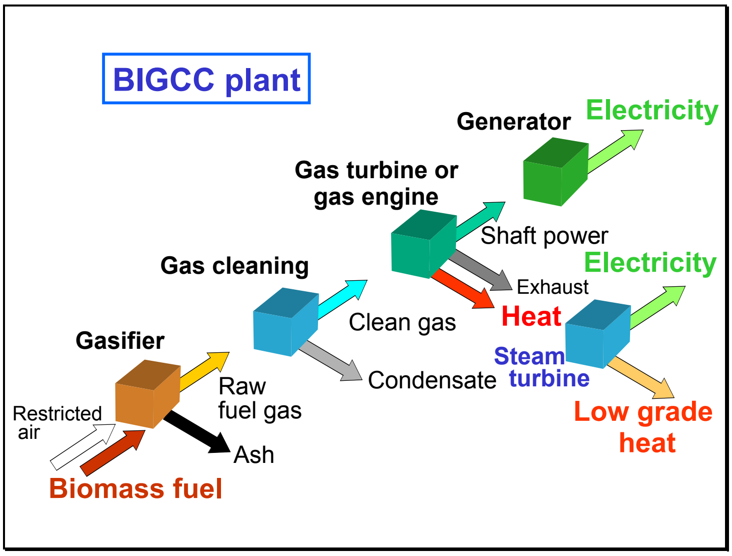

Figure 14-7 BIGCC plant concept

The attraction of such systems is electrical efficiencies significantly greater than many other bioenergy systems. In the decade up to around 2002 several large demonstration projects were developed in the range of 7-10MW$_e$. However, none of these plants went into extended operation and BIGCC has not moved beyond the large-scale demonstration phase.

14.7.6 Conversion of pyrolysis oil

Pyrolysis oil (Bio-oil) and its upgraded products are potential substitutes for heavy and light fuel oil (including diesel) in stationary energy applications including in boilers, furnaces, engines and turbines for electricity and co-generation applications. In addition, a range of chemicals can potentially be extracted or derived from bio-oil including food flavourings, specialty chemicals and resins. The main prospect and research area for bio-oil is its further processing and upgrading for transportation fuel. This is covered in Chapter18.

Bio-oil has potential for electricity production in boilers, engines and combustion turbines. As has been noted already, bio-oil can be produced in one location and transported to a power plant located elsewhere. Bio-oil has a number of environmental advantages over fossil fuels such as diesel:

- Reduced carbon dioxide emissions. Bio-oil is derived from biomass, which when sustainably produced emits no net greenhouse gases.

- No SOx (oxides of sulphur) emissions, as biomass contains virtually no sulphur
- Potential for low NOx (oxides of nitrogen) emissions. Bio-oil fuels are reported to generate under half the NOx emissions of diesel oil in gas turbines.

Canadian companies Dynamotive and Ensyn have both demonstrated the use of bio-oil as a fuel for furnaces.

Bio-oil has been successfully demonstrated in trials on various engines, ranging in size from laboratory test units to 1.5 MW_e modified dual fuel diesel engines. In 2000 Ormrod of the UK reported that it had successfully operated a low speed, dual fuel, 250 kWe engine on emulsions of bio-oil and diesel fuel for a number of trials that totalled over 400 hours of operation[6]. Trials were also completed running exclusively on bio-oil. Wartsila of Finland ran tests in 1995 but determined that further R&D was required prior to commercialisation[7]. A white paper by Ensyn indicates the potential benefits of power production using engines and bio-oil as fuel, with the higher relative efficiencies of engines potentially providing greater electricity generation than a steam cycle plant for the same amount of biomass feed[8].

Dynamotive and Orenda have demonstrated operation of a 2.5 MWe industrial gas turbine fuelled on bio-oil in Canada. In the Netherlands, turbine supplier OPRA has conducted combustion tests using oil supplied by BTG[9].

14.7.7 Fuel cells

Fuel cells are electrochemical devices in which a hydrogen-rich fuel reacts chemically with oxygen to produce electricity and heat. Fuel cells have some similarities to batteries, except that the energy source (fuel supply) is continuously replenished during operation. During the past 10 years in particular, progress on fuel cells has been considerable, primarily due to the development of new catalysts and materials. While they are not yet in broad commercial use, their market entry is now considered by many to be imminent, with some proponents considering them to be the most likely future alternative to internal combustion engines for both vehicle and stationary power and heat applications.

A fuel cell system consists of several major components including:

- a hydrogen fuel supply or, if hydrogen is not used directly, a fuel reformer to generate hydrogen-rich gas from the chosen fuel
- a power section where the electro-chemical process occurs

Following generation, a power conditioner may be used to convert the direct current (DC) generated in the fuel cell into alternating current (AC).

The power section consists of the actual stack of fuel cells linked in series. Each cell consists of an anode and a cathode in contact with an electrolyte and operates essentially by reverse electrolysis. When the anode and cathode are supplied with hydrogen fuel and air respectively, the fuel cell generates a voltage between the two electrodes of less than 1V peak. When the electrodes are connected to an external circuit the fuel cell generates electric power

The chemical equation:

$2H_2 + O_2 \qquad 2H_2O + \text{energy} \qquad \longrightarrow$

is the same for when hydrogen is combusted in air but instead of light and heat being produced, electrical energy is generated, together with varying degrees of heat.

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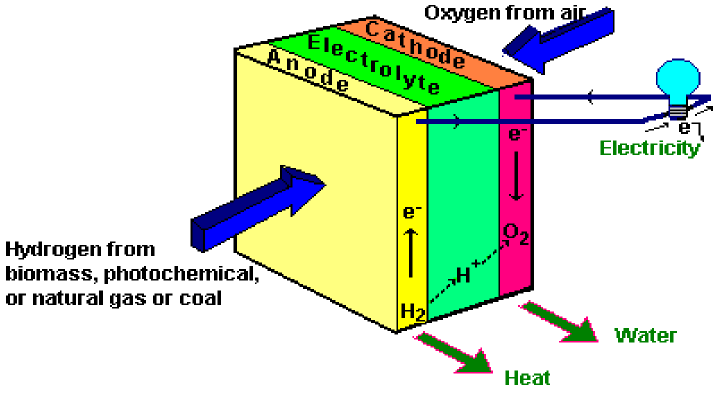
[6] http://www.pyne.co.uk/Resources/user/PyNews%2010.pdf

[7] http://www.redbiomasa.cl/images/documentos/Seccion%207%20-%20Haga%20-%20Planta%20de%20generaci%C3%B3n%20el%C3%A9ctrica%20con%20aceite.pdf

[8] http://www.ensyn.com/wp-content/uploads/rich-widget/file/Envergent_Electricity_5406_EN_WP_10v2.pdf

[9] http://www.btgworld.com/en/rtd/technologies/energy-from-pyrolysis-oil



Source: Energy Wise News, EECA

Figure 14-8 Operating principle of a fuel cell

Individual fuel cells produce only between 0.5-0.9 volts of DC electricity so they are combined into stacks like cells in a battery to obtain more usable voltage and power outputs.

Advantages of fuel cells include:

- high energy efficiency, even in the lower power range
- modular design, enabling different power ranges to be obtained
- very low emissions
- low maintenance and high reliability, as there are no moving parts
- no noise from the fuel cell.

Fuel cell technologies differ with respect to their electro-chemical reactions, materials of construction, tolerance to contaminants, fuel flexibility, and operational characteristics. These characteristics vary with the application and the cost. For applications in transport, fuel cells are required with high performance, but moderate lifetimes are acceptable since vehicles have a relatively short life. Stationary applications are more demanding on lifetime, but less so on power density.

The efficiency of fuel cells remains essentially the same irrespective of power plant size. Due to flexibility in plant size, both small and large power plants can be installed in either congested urban dwellings directly connected to the grid or in relatively small or isolated villages, islands and utility centres as ‘stand alone’ systems.

Fuel cells are currently considerably more expensive than ICEs. However it is claimed that, in the long term, the cost of electricity generated from fuel cells will become less than from other competing energy conversion systems such as ICEs. This will in part be due to flexibility of the fuel source, and increased efficiency.

Australian company Ceramic Fuel Cells Limited is a leader in the development and commercialisation of solid oxide fuel cells and has developed a mini CHP system, BlueGen™ for domestic and commercial applications based on natural gas. These systems provide a net output of up to 2kW electricity and operate at an efficiency of 60 percent.

Hydrogen, the ideal fuel for fuel cells, can be produced from a wide range of renewable and non-renewable sources. While natural gas is generally the cheapest fuel from which hydrogen may be produced, biomass feedstocks can also be used to produce hydrogen. To obtain hydrogen from biomass a process of pyrolysis or gasification must be applied, which produces a gas containing approximately 20% hydrogen by volume.

The dual challenges facing fuel cells at present are for the cells to reach a point where they are commercially competitive with other more established forms of generation, and to overcome the separate economic barriers that current technology presents for converting biomass to hydrogen for use in such devices.

14.8 **Discussion**

At present approximately 90 percent of bioenergy worldwide is produced in combustion units. Boilers raise steam to power steam turbines, which in turn drive turbo-alternators. The maturity of this technology may be gauged by the level of deployment where for instance, in the USA alone there is some 12,836 MW[10] of installed bioenergy capacity of all forms. Australian examples of the application of biomass combustion technology include the 30 MWe cogeneration plants at Condong and Broadwater in NSW, which operate on sugar cane bagasse and supplementary wood waste fuels.

At a smaller scale, there are many examples around the world of gasifiers supplying gas feed to internal combustion engines, driving small generators. International examples of this technology include the gasifiers supplied by Martezo and Xylowatt from Europe and Ankur in India, all fuelling spark ignition engines up to the 0.5 MW scale. In Australia companies such as Gasification Australia and Real Power Solutions have been developing small scale biomass gasifiers.

The quest for more efficient, industrial scale bioenergy has led to the development of high efficiency fluid bed boilers for large heat and power applications[11]. It has also led to investigation of biomass integrated gasification combined cycle plants, although no such units operate commercially. Other developments are small modular generation units such as Organic Rankine Cycle generators now starting to be used in saw mills in Australia.

To overcome a thermodynamic limitation to the efficiency of conventional ‘heat engines’, fuel cells are being developed to achieve greater energy conversion of the fuel. It is possible that once this type of technology is commercialised for use with natural gas, it will also be adapted to run off purified biogas and syngas derived from biomass.

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[10] U.S. Energy Information Administration, http://www.eia.doe.gov/cneaf/electricity/epa/epat1p2.html, updated 4 January 2011.

[11] http://www.fwc.com/publications/tech_papers/files/TP_BFB_11_01.pdf

15. Costs for electricity

15.1 Summary

Key determinants for the cost of electricity from a biomass plant are:

- the economy of scale of the plant
- impact of biomass fuel costs
- maximising the running time of the power plant.

These concepts may be illustrated by considering three hypothetical bioenergy plants of different scale and configuration. These are a 500 kW gasification plant (based on automated European equipment) fuelling a reciprocating gas engine that drives a generator, and 5 and 20 MW plants with conventional boilers and steam turbines producing electricity. An assessment of the feed requirements, capital costs and operating costs per year is summarised as follows:

Table 15-1 Assessment of costs per year

	500 kW	5 MW	20 MW
Gross electrical output (MWe)	0.55	5.5	21.6
Feed requirements (green kt/yr)[1]	9.1	78.7	280.8
Capital cost (M$)	$3.9	$27	$63
Operation & maintenance cost (M$/yr)	$0.22	$1.6	$3.4
Unit capital cost ($M/MW)	8.4	5.4	3.1

This table illustrates the significant benefits of economy of scale in larger plants, with the per-megawatt capital cost for a 20 MW plant only 40 percent that of the cost for a 0.5 MW plant. Smaller plant projects generally have a proportionately higher fixed development cost, and for a 0.5 MW project the basic plant and equipment cost may comprise only two-thirds of the completed project cost.

A simple costing model may be used to assess the required electricity selling price to make a bioenergy project financially viable. The model uses a set of baseline assumptions, such as project life, construction period, inflation rates for costs and revenues, depreciation, financing rates for debt, feed purchase price (assumed to be $50 per green tonne at the bioenergy plant), operating time per year and the required internal rate of return (IRR) to attract investment.

With suitable assumptions made for these parameters, the required electricity selling prices for financial viability at the various plant sizes are: 1MW: $310/MWh; 5 MW: $230/MWh; 20 MW: $160/MWh. The cost components attributed to feed purchase, operating cost, capital cost and required return are shown in Figure 15-1.

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[1] 50% MC wb

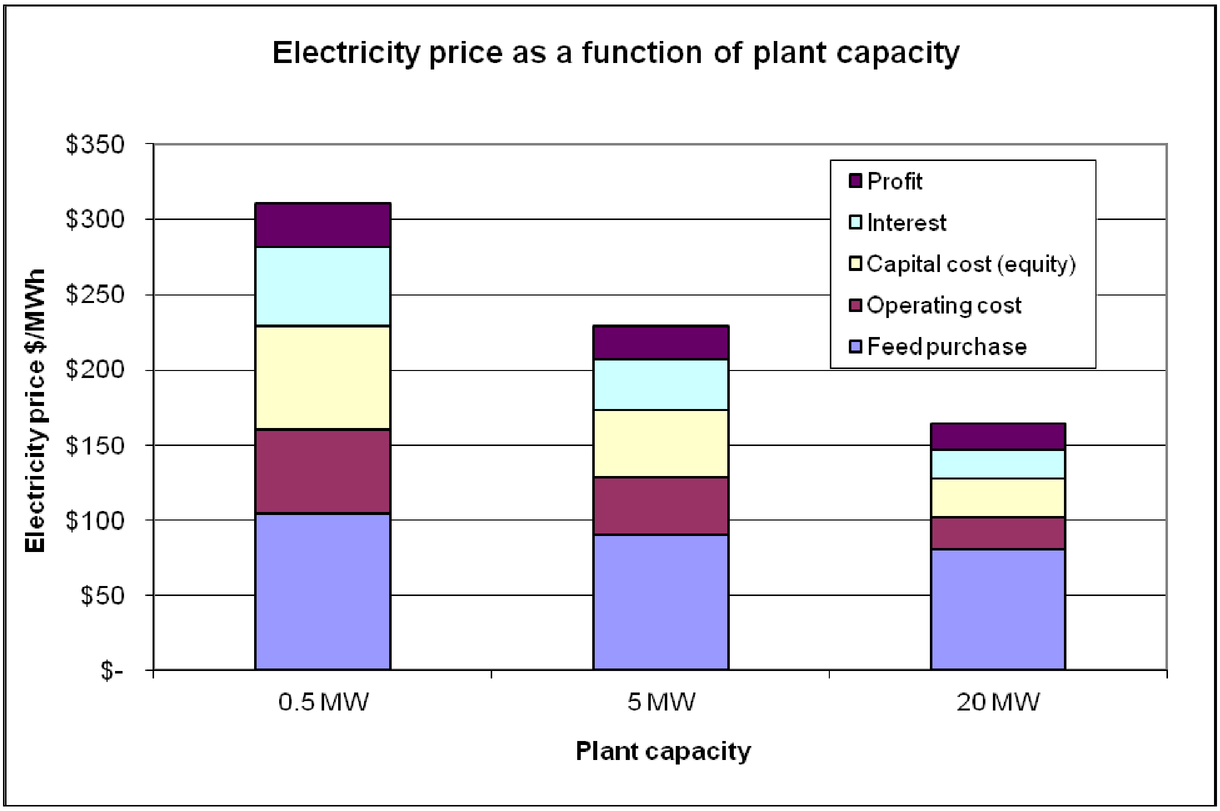

Figure 15-1 **Electricity price as a function of plant capacity**

For small projects, capital cost is the major cost element, making it important that use of the plant is maximised to improve fixed cost recovery. For large projects, the unit capital cost has dropped and the largest single cost is expected to be feed purchase. Low feed costs via use of low value residues (such as sugar cane bagasse), or revenue due to feed co-values, could provide opportunities for commercially viable some projects.

When modelling these projects, costs may be varied to show the sensitivity of the financial model to each major cost. The price required for electricity sales is found to rise linearly with increasing feed cost, drop with increased utilisation of the plant, rise with increases to capital, operating and maintenance costs, and rise with increased levels of equity as opposed to debt finance.

15.2 Introduction

This chapter provides an introduction to the costs of electricity generated by different sized bioenergy plants. It highlights key issues that can have a major impact on the electricity cost, including:

- The economy of scale provide by the bioenergy plant
- The impact of the feed cost
- The importance of running the plant for as many hours per year as possible.

These data should only be used as a general guide. They include assumptions as to equipment, site, feed characteristics, labour requirements and so on which, while selected here to be broadly representative, could vary significantly from project to project. Nevertheless, the information presented in this chapter can help to identify:

- Whether an opportunity is worthy of more detailed analysis
- The areas of the potential project that show greatest sensitivity to variations, and thus warrant the most attention in any investigations.

To show the variability of costs and sensitivities with project size, three plant of different size are presented. These have been selected arbitrarily and have electrical outputs of:

- 0.5 MW, utilising gasification and gas engine technology
- 5 MW, utilising conventional boiler and steam turbine technology, with air-cooled condenser
- 20 MW, utilising conventional boiler and steam turbine technology, with water-cooled condenser and cooling towers

The main parameters for each of these options are shown in Table 15-2.

Table 15-2 Electricity plant parameters

	500 kW	5 MW	20 MW
Gross electrical output (MWe)	0.55	5.5	21.6
Feed requirements (green kt/yr)[2]	9.1	78.7	280.8
Capital cost (M$)	$3.9	$27	$63
Operation & maintenance cost (M$/yr)	$0.22	$1.6	$3.4

These costs are analysed later in this chapter to develop prices for electricity.

15.3 Capital costs

The capital cost breakdown for each option is shown in Table 15-3.

Table 15-3 Breakdown of capital costs

Electrical output	0.5 MW	5 MW	20 MW
	Cost estimates		
Feed handling	included	$ 400,000	$ 6,700,000
Gasifier	$2 600 000	-	-
Boiler	-	$ 14,600,000	$ 20,600,000
Steam turbine	-	$ 4,000,000	$ 9,600,000
Auxiliary equipment	$ 200,000	$ 200,000	$ 3,300,000
Grid connection	$ 200,000	$ 2,100,000	$ 3,100,000
Civils and infrastructure	$ 300,000	$ 1,300,000	$ 6,800,000
Design and proj. management	$ 400,000	$ 1,000,000	$ 2,100,000
Contingency	$ 500,000	$ 3,500,000	$ 10,400,000
Total	$4,200,000	$27,100,000	$62,600,000
Unit cost ($M/MW):	8.1	5.4	3.1

The cost shown for a 0.5 MW gasifier is for a package plant from European suppliers comprising feed drying, gasification and engine/generator set.

1. Auxiliary equipment includes such items as mobile plant and cooling towers.

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[2] 50% MC wb

2. Design and project management includes owners engineering, commissioning and permitting costs.

3. The contingency allowance is selected to match the accuracy of the other cost components.

The economy of scale achieved with larger plants is clearly seen from these three examples, with the unit capital cost at 20MW only 40% of the cost for a 0.5 MW plant.

Also, the difference between equipment costs and a completed, installed project may be quite significant. For example, the basic equipment for a straightforward 0.5 MW project may only comprise two thirds of the completed project cost.

15.4 Operating costs

Apart from the purchase of biomass feed, the principal operating costs for a bioenergy plant are for operating labour, maintenance and consumable items. A typical operating cost breakdown for each of the three plant sizes is shown in Table 15-4.

Table 15-4 Breakdown of operating costs

	0.5 MW	5 MW	20 MW
Operational labour	$ 55,000	$ 470,000	$ 930,000
Maintenance	$125,000	$ 810,000	$ 1,880,000
Consumables	$ 40,000	$ 270,000	$ 620,000
Total	$220,000	$1,550,000	$3,430,000

The job roles and numbers that have been assumed for each option are shown in Table 15-5.

Table 15-5 Labour cost breakdown

Position	$/person/year	Number of positions		
		0.5 MW	5 MW	20 MW
Clerk	$ 60,000		0.2	1.0
Plant Manager	$100,000		0.5	1.0
Tradesman	$ 80,000		0.5	1.0
Plant Operator	$ 70,000	0.5	1.0	4.0
Boiler Attendant	$ 80,000		4.0	4.0
Shift Relief	$ 90,000		0.5	1.0
Head Office Costs	$ 80,000	$20,000		
Total		$55,000	$470,000	$930,000

The plant operator and boiler attendant positions for the 5 and 20 MW plants are shift positions and therefore require shift relief (to cover sickness, holidays etc). All other positions are day positions. Note that the number of personnel required can vary significantly with different feed characteristics and handling requirements and opportunities to “share” personnel with other, adjacent processing facilities. Modern plants in Australia tend to favour low labour usage and a high level of automation (as opposed to plants in other parts of the world where the cost of labour may be lower). For small plants in particular, the ability to operate unattended can have a major impact on project viability.

Annual maintenance costs are estimated as 3% of the total capital cost. Recommended allowances from individual suppliers can vary considerably both in scope and amount. In many cases, routine maintenance may be undertaken by plant personnel. In other cases, it needs to be completed by specialists. Maintenance costs are very sensitive to the location of the plant, and the skills and availability of local tradesmen.

Consumable costs are estimated as 1% of the total capital cost, and cover such items as boiler and domestic make up water, effluent disposal, and workshop and office consumables.

15.5 Costing model

The commercial decision to build a bioenergy plant is made on a similar basis to a decision on any other large industrial project. When a company or investor is asked to provide money to enable a bioenergy plant to be built, it is essential that they can understand the way that the project will be developed and the time expected for their investment to be recovered and profit realised. Table 15-6 shows typical assumptions used for simple financial analysis of the bioenergy plants described above.

Table 15-6 Assumptions used for the economic analysis of bioenergy systems

Item	Value used
Project life	15 years from first investment
Residual value of plant	Assumed to be nil
Construction period for the plant	12 months for 0.5 MW option 18 months for 5 MW option 24 months for 20 MW option
Commissioning period	included in construction period
Production ramp up	Immediate full production and full product purchase
Inflation of costs and revenue each year	2.75% for costs 2.75% for revenue
Depreciation	straight line over 15 years
Company tax rate	28%
Interest on any borrowings	10%, with principal repaid at end of project
Financing	50% equity financing
Feed purchase price	$50 per green tonne with 50% moisture content, delivered to site in chipped or hogged form
Plant operation	8,000 hours per year (leaving time for scheduled shutdowns and maintenance)
Required project IRR	15% after tax
Working capital	not included

15.5.1 Price of electricity

Using assumptions such as those above described above, and the typical capital and operating costs for each bioenergy plant, allows calculation of the necessary price for sale of electricity to achieve financial viability so that the project may proceed. These prices are shown according to plant output in Table 15-7.

Table 15-7 Results of economic analysis

Plant size	Required electricity sales price
0.5 MW	$310 / MWh
5 MW	$230 / MWh
20 MW	$160 / MWh

The profit, interest, capital cost (equity), operating cost and feed purchase cost components of the above mentioned electricity sales prices are shown in Figure 15-2 to demonstrate how these component portions change with increasing plant size.

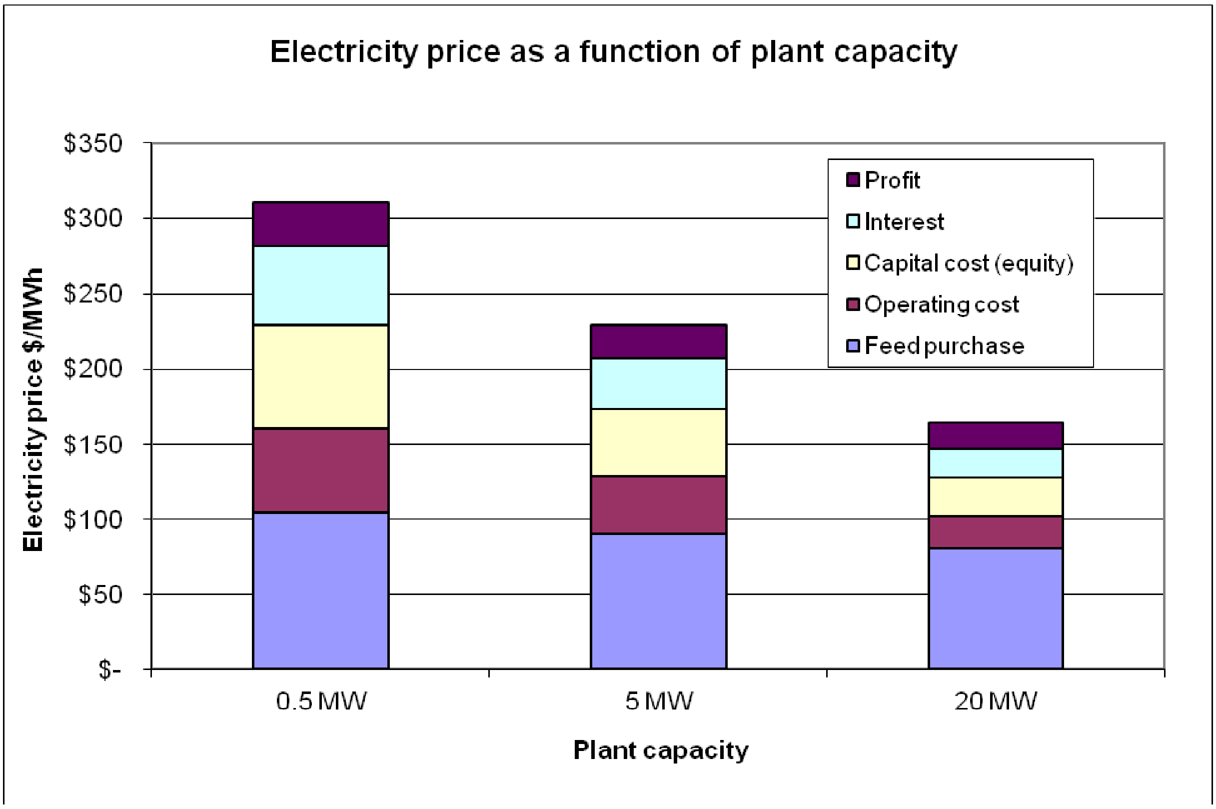

Figure 15-2 Electricity price breakdown

This process will allow an investor to achieve a certain internal rate of return on his investment (set at 15% after tax for this example). An alternative way to assess the project is to consider the price for electricity that is acceptable in the marketplace and determine what IRR that will provide. If the IRR is high enough an investor may finance the plant.

While prices paid to generators for renewable electricity are usually confidential to those involved, it is understood that grid-based baseload renewable electricity, with Renewable Energy Certificates, is typically purchased at prices in the vicinity of $100/MWh. Thus, none of the above projects would be deemed financially viable for any investor seeking a return of 15% or greater. To determine what may be changed about a project to improve its viability involves an examination of the sensitivity of the financial performance to changes in the major project variables. Several of these are considered below.

15.5.2 Electricity - sensitivity analysis

The figures shown above for bioenergy projects represent one set of conditions for each example. It is quite likely that conditions will vary considerably from project to project, or even within a project over time. Equally, in the early stages of development it is understandable that there will be some uncertainty over the costs being used to determine project viability and the organization developing the project will wish to understand the effect of changes that might occur to the financial data as the project progresses. For these reasons it is useful to conduct sensitivity analyses, looking at the impact of changes to key project parameters. These changes may be examined singly or in combination.

To illustrate this aspect of project appraisal, a number of sensitivity analyses were performed on the bioenergy plants described above. In each case a single major parameter was varied and the effect of the change was plotted against electricity selling price. Variables examined were:

- feed cost
- plant utilisation
- plant capital cost
- operating and maintenance costs
- revenue inflation
- portion of equity financing
- term of loan.

The results of these sensitivities are shown in Figure 15-3 to Figure 15-10

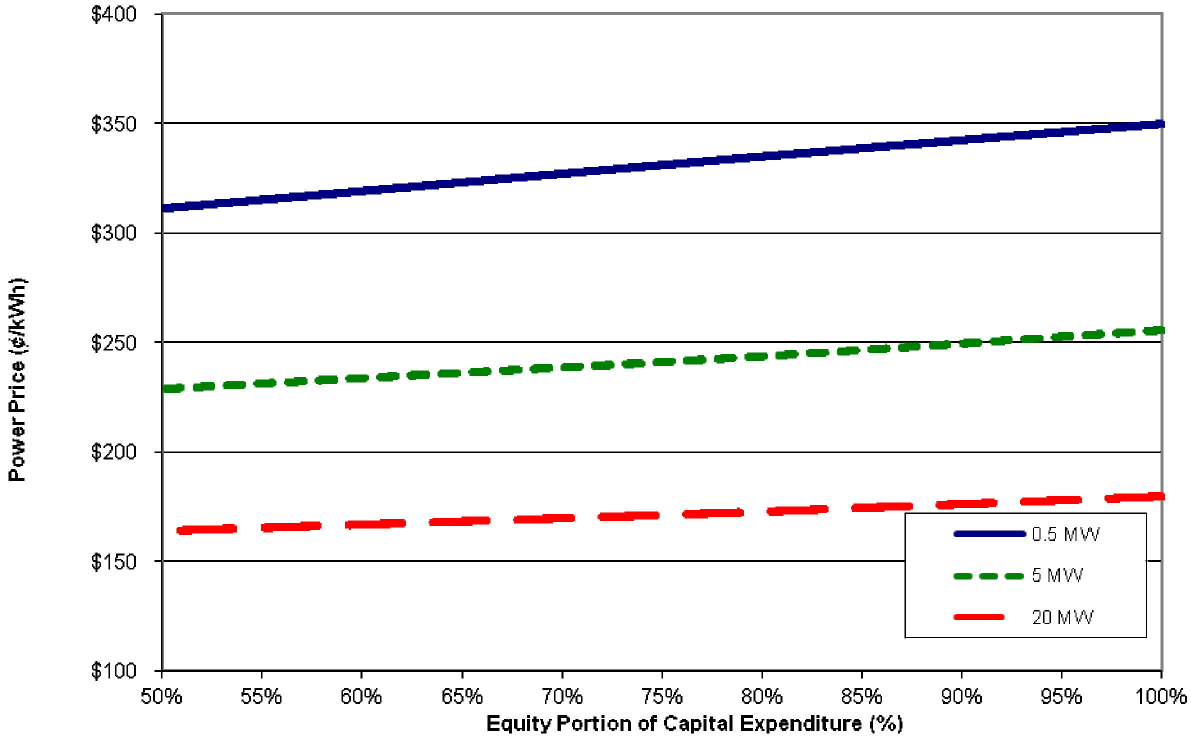

Figure 15-3 **Equity portion of capital expenditure**

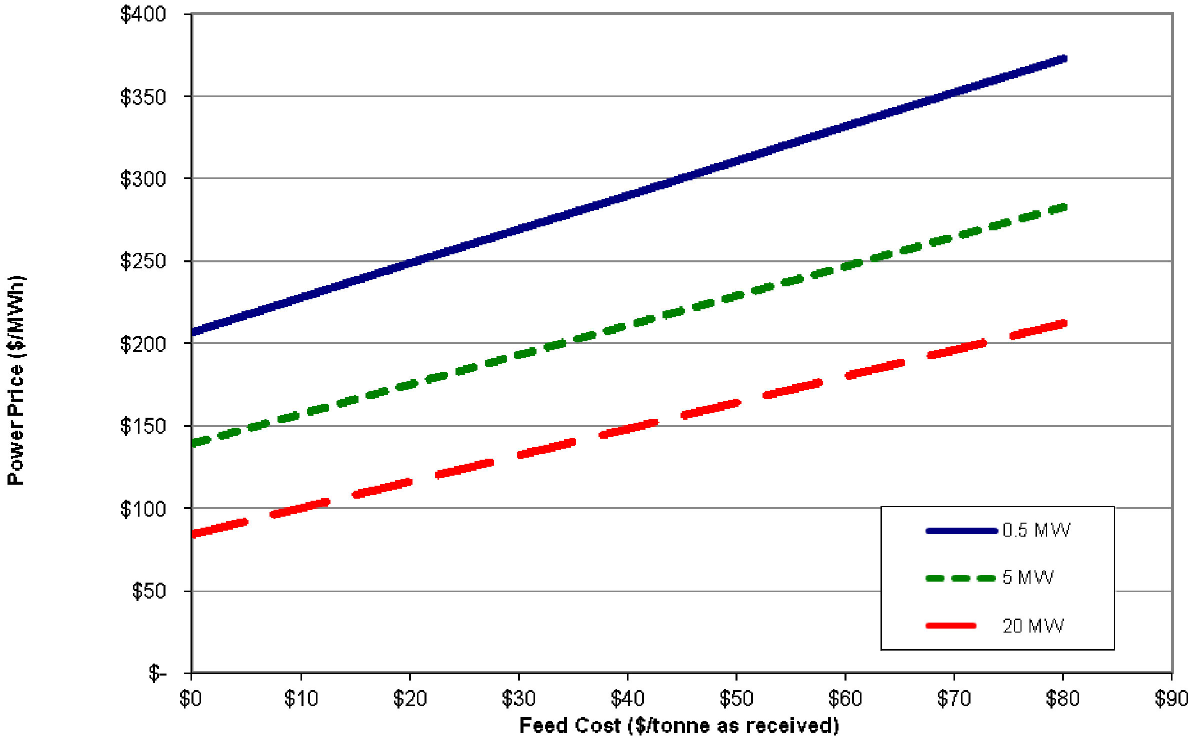

Figure 15-4 **Power price variation due to feed cost changes**

Changes in feed cost create proportional changes in electricity selling price. A $10 change in feed price is reflected in a change to the required electricity selling price of $16-21/MWh, depending on the system efficiency. These curves are developed for fresh (i.e. green) wood feed.

For low feed costs some of these hypothetical bioenergy projects could offer electricity that is quite competitive with other sources of renewable power. An understanding of feed cost (and all of its elements) is therefore central to both the development and implementation of a bioenergy project. In many cases the variability in feed cost may be more significant to assessing viability than all other costs for the project.

When bioenergy projects are discussed, there is often talk of “free” feed, in the form of agricultural, forestry or processing residues. Note that the financial viability of a bioenergy project is based on the cost of feed actually delivered to the bioenergy plant. This includes any cost of feed purchase, plus collection, transport and possibly intermediate storage, preparation (size reduction) and possibly also drying. Thus feed with nil value at its source (e.g. saw mill residues) may have a cost of $50/tonne or more by the time all costs are included.

Note also that bioenergy projects can only be seriously considered when feed supply is secure for the life of the project (typically at least 20 years). No sensible developer will commit millions of dollars to a power plant if there is too much uncertainty about cost and/or availability of feed once the project is built. But when the initial cost of the feed is close to zero, there is little incentive for the producer of that feed to enter into long-term supply agreements. The dynamics of feed supply and project risk need to be well understood before any project can proceed.

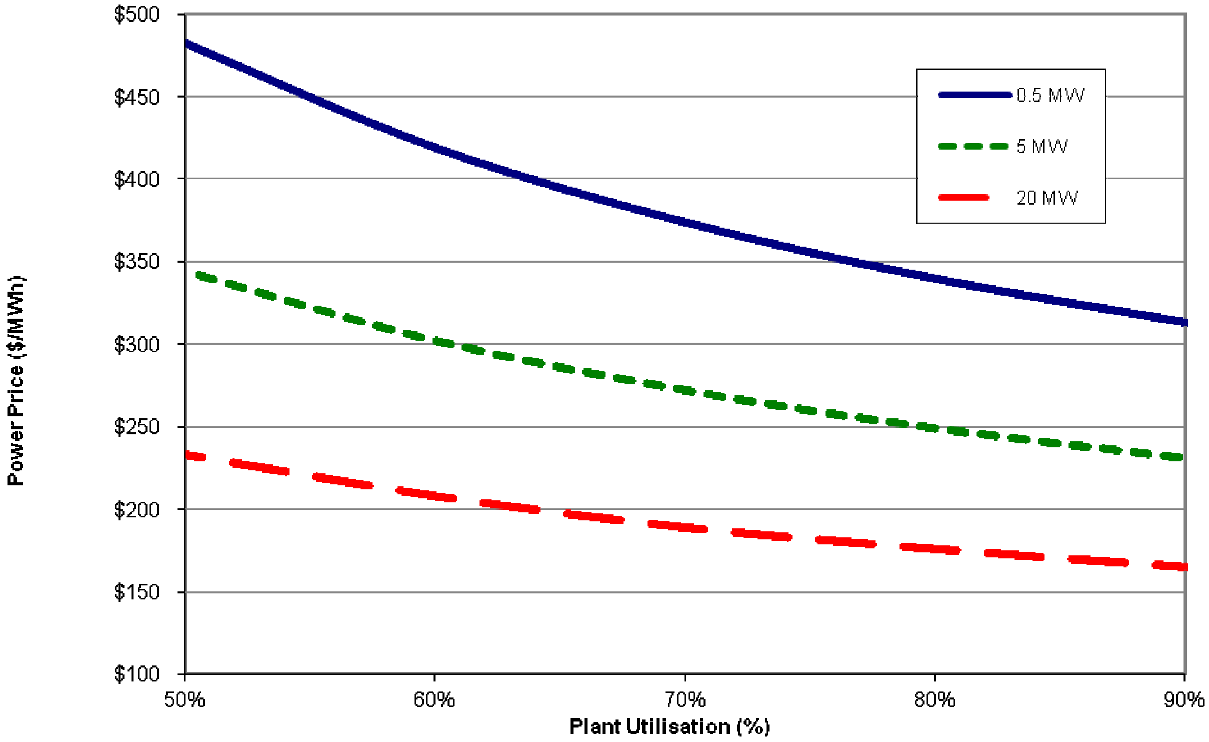

Figure 15-5 **Power price variation due to plant utilisation changes**

Plant utilisation is the amount of time over a given period that the plant will be operational and fully utilised. No plant can operate for 24 hours per day and 365 days per year; there is a need for maintenance and repairs, both scheduled and unforeseen. Thus many large fossil fuel power stations operate for approximately 90% of the total time available each year. Many bioenergy plants are capable of similar levels of performance. In the base cases described above it was assumed that a bioenergy plant would be operational and providing maximum electricity for 8,000 of the 8,760 hours available each year, representing 91% utilisation.

If a small-medium power plant is connected to a large electricity grid it is likely that the full output of the plant can be utilised whenever the plant can operate. However, if a power plant is isolated from a large grid, its output may be restricted by the changing needs of the particular users it supplies. This may mean that there are times where it is required to operate at less than full output or even go offline. Reducing the overall utilisation can have a major effect on the cost of electricity needed to maintain a certain IRR. As the graph above shows, a drop from 90% to 50% utilisation will force the price of electricity up by about 50% if commercial returns are to be maintained.

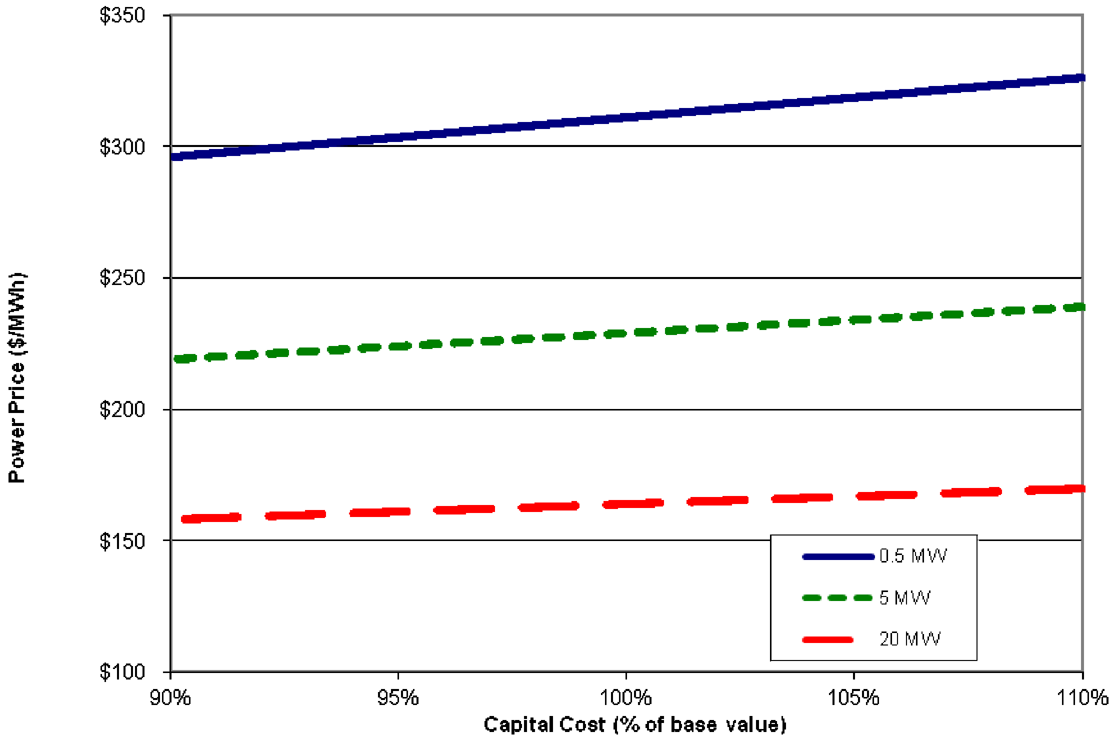

Figure 15-6 Power price variation due to capital cost changes

There are many factors that will cause variations in capital cost between two plants of similar capacity. These can include:

- location difference, requiring different site preparation and civil works, or different labour rates for construction
- access to electricity grid requiring new lines, associated grid infrastructure, etc
- feed storage and preparation requirements
- different feed conditions, or expected variation in feed parameters, resulting in different combustion or gasification equipment
- emission control, by the design and installation of equipment to keep gaseous, liquid, solid and noise emissions to acceptable levels
- synergies in co-location alongside existing facilities – share personnel, equipment, infrastructure etc
- co-generation requirements
- selection of equipment configuration that increases reliability or decreases risk of down time but is more costly to build (for example using dual fuels or installing multiple engines instead of just one).

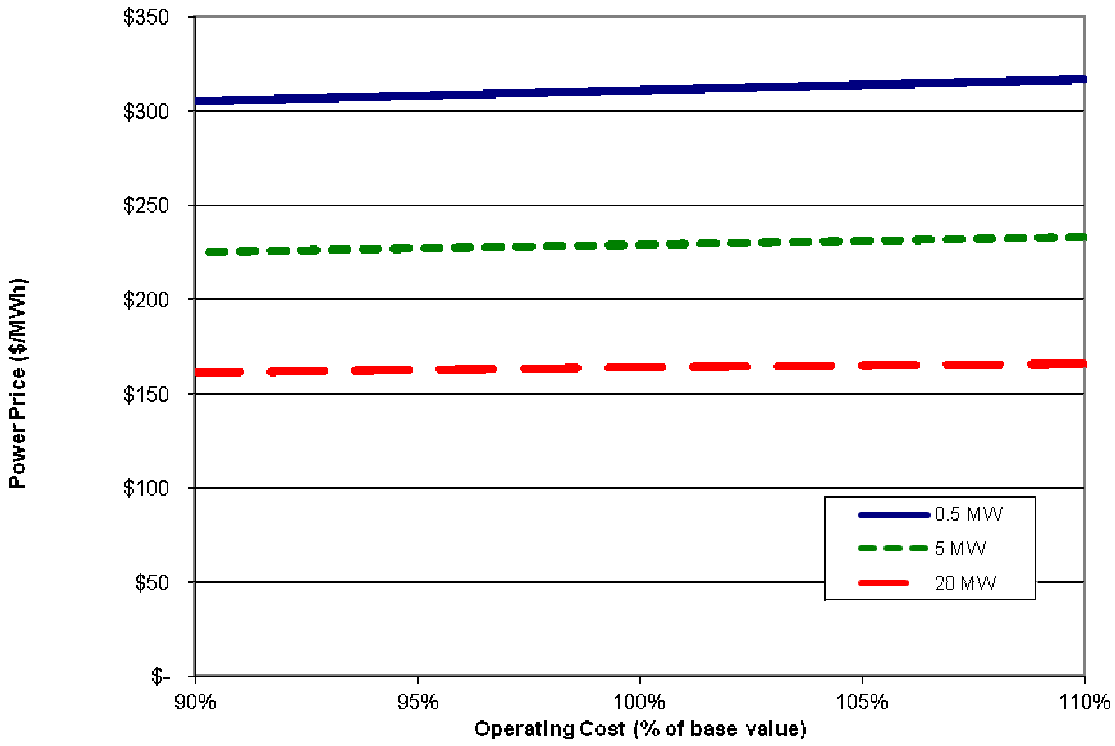

Figure 15-7 Power price variation due to operation and maintenance cost changes

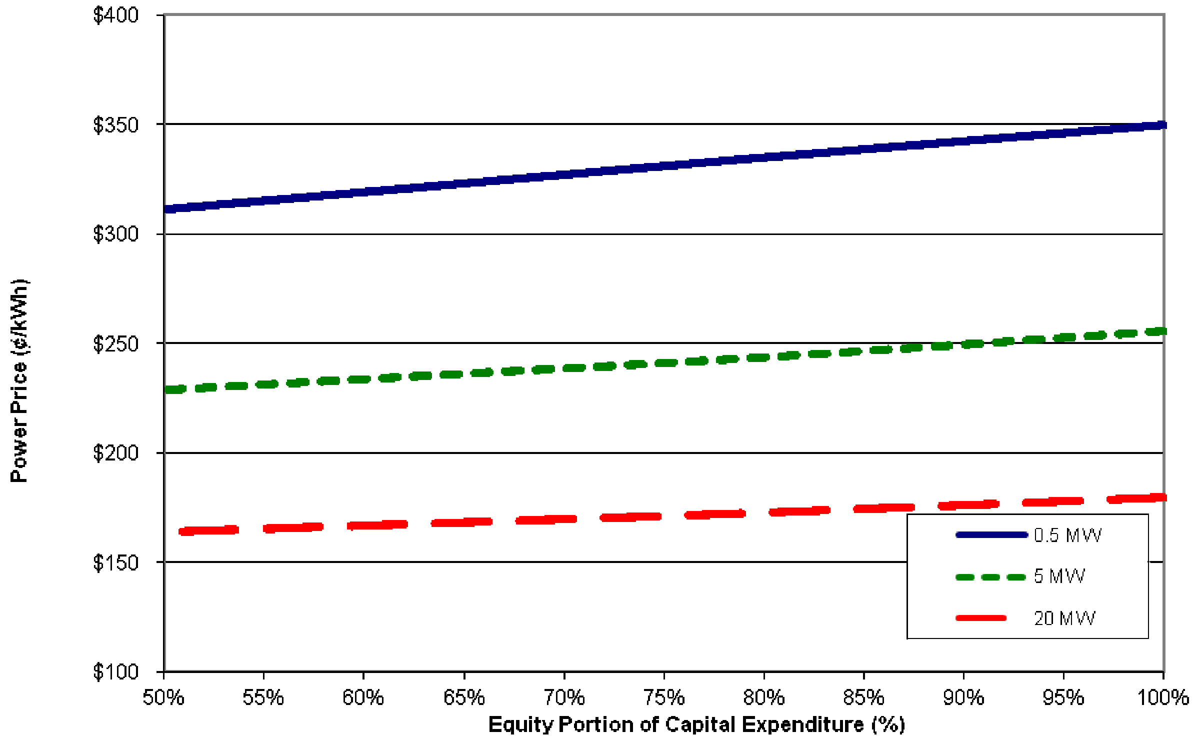

Figure 15-8 Power price variation due to equity portion of capital changes

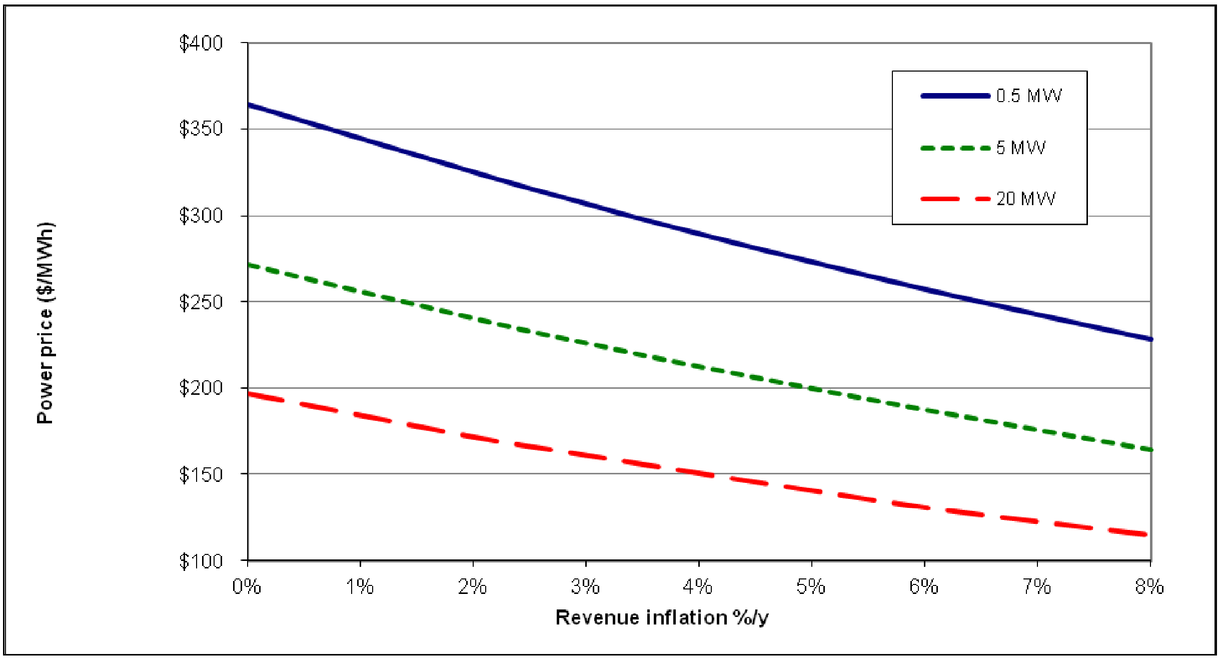

Figure 15-9 **Power price variation due to revenue inflation**

The value assumed for revenue inflation has a major effect on the viability of a project. When selecting a value, one needs to consider factors such as:

- those that will affect the alternative means of generating electricity at a particular site, i.e. diesel prices are likely to increase as the supply of oil tightens, while the supply of coal is not limited in the medium term.
- government policy, e.g. the quantity and price of RECs.

Financing options have an effect on the viability of a project. Figure 15-10 shows the effect of 3 different financing options:

1. No debt
2. A loan for 50% of the capital, repaid over 5 years.
3. A loan for 50% of the capital repaid at the end of the project.

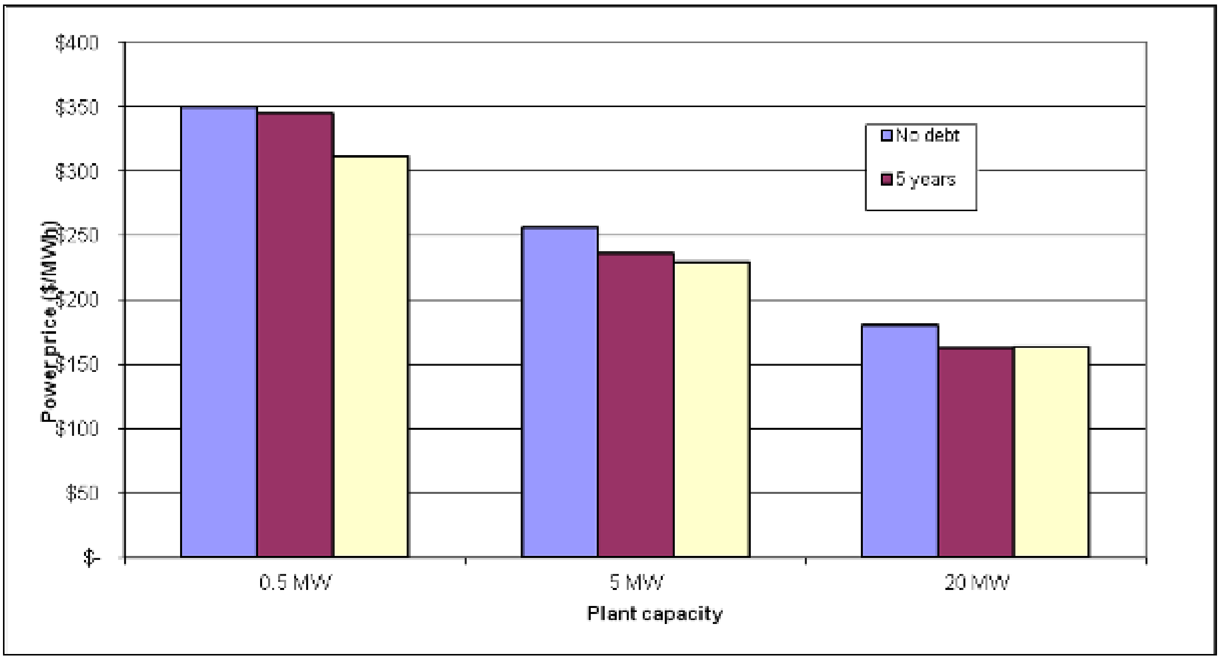

Figure 15-10 Power price variation due to term of loan

15.6 Discussion

There are other project parameters that may be varied, for example the rate of return for project investors. Projects with secure feed supply and long-term (more than 5 years) power purchase agreements may be able to attract investment capital at lower returns and debt over longer periods, both of which will assist the commercial viability of the project.

Even with funding at competitive rates, good plant utilisation and low cost feed, it is clear from the above data that many potential electricity projects will not be financially viable. This will be particularly true for smaller projects (with higher unit capital costs) and projects with significant costs for biomass feed.

Against these difficulties, niche opportunities may be possible, for example in locations that are off-grid or where a premium may be paid for electricity due to difficulties in grid supply

The difficulty in achieving financial viability based on electricity sales alone also points to the importance of finding:

- cogeneration opportunities, such those already achieved in the sugar industry and parts of the wood and pulp& paper industries.
- co-products
- value for additional environmental and/or social benefits.

15.6.1 Small scale or large scale generation?

If sufficient biomass is available it is clear from the examples above that, for a given cost of biomass and return to investors, a large scale power plant will produce cheaper electricity than a small scale plant. This should not come as a surprise as it mirrors almost every other processing industry in the world, where economies of scale lower the unit costs of production and make a business more competitive.

However, this does not mean that small scale power plants have no role to play. In many situations they may be linked to limited supplies of biomass or customers with specific needs for electricity and heat, such as saw mills and sugar mills. In many parts of rural Australia the local electricity grids are not built with enough capacity to accommodate a large electricity generator, and the economies of scale achieved by a large plant may be diminished by significant costs to upgrade an existing transmission line or build a new line to take the electricity to its customers.

15.6.2 Distributed or centralised generation?

It is sometimes suggested that the cost of biomass transport will justify building small, distributed power plants rather than large centralised facilities. In other words, it is may be more commercially attractive to build small plants close to biomass than to transport the biomass long distances to a large plant. To explore this premise, consider the 5 MW and 20 MW bioenergy plants described above.

Figure 15-4 above shows the relationship between feed cost and power price for hypothetical plants of 5 MW and 20 MW capacity. For the same return to investors and an electricity selling price of \$150/MWh, the 20 MW plant can purchase feed at approximately \$43/green tonne while the 5 MW plant can afford to pay approximately \$6/green tonne. Theoretically the difference of \$37/tonne could all be applied to transport to supply biomass to the larger, centralised plant. If wood chip feed can be transported to the larger plant at a marginal cost for extra transport of 10 cents per tonne per km, the larger plant can afford to transport its biomass more than 300 km further than the small plant and still be more competitive. While this is just one example, it highlights that the premise of transport distance being more important than plant capacity should be tested very carefully during project feasibility work.

16. Characteristics of biofuels

16.1 Introduction

This chapter examines the physical and chemical characteristics of the main types of biofuels and makes comparisons with fossil fuels, which they aim to displace or with which they may be blended.

- The main conventional types of fossil fuels are diesel and petrol (also known as gasoline, especially in north America). Petrol is used in spark ignition internal combustion engines, while diesel is used in compression ignition internal combustion engines.
- The most widely used biofuel at present is ethanol. This is blended with petrol, generally to the ten percent level (E10), but also in higher blends (E85) that require specifically-constructed “flex fuel” engines and fuel systems.
- Another biofuel already widely used is biodiesel, which may be blended with petroleum diesel to five percent (B5) without significantly modifying the properties of the diesel fuel. Blends beyond B20 may require relatively minor modification of fuel systems, especially in older vehicles.

Existing biofuels (particularly ethanol from sugar and starch and biodiesel from oilseeds or waste fats and oils) are often called first generation fuels. The terms second, third and fourth generation fuels are used to describe new (still pre-commercial) fuels derived from biomass or algae and fuels made in multi-product biorefineries. The term “advanced biofuels” captures all of these new fuel types and differentiates them from existing, first generation fuels.

Definitions for advanced biofuels vary in their detail:

- The US renewable fuel standard, passed under that country’s Energy Independence and Security Act of 2007, defines advanced biofuel as any renewable fuel that meets a 50 percent life-cycle GHG emissions reduction from the petroleum baseline, and is not derived from corn starch.
- In their 2011 Australian report[1], LEK define advanced biofuels as liquid fuels derived from sustainable sources of organic matter that do not typically compete with food production, such as wood residues, certain oilseeds, and algae.

Advanced biofuel feedstocks include woody biomass, agricultural and food-processing residues, energy crops, non-food oilseeds and algae. Municipal wastes are also recognised as feedstocks. All of these materials can include cellulose, hemicellulose and lignin, or oils in the case of oilseeds and algae.

There are many different advanced biofuels under development to increase the scale of biofuel production.

- Some of these new biofuels are chemically identical to existing ethanol and biodiesel.
- Others are hydrocarbons that are chemically very similar to existing fossil fuels and capable of being used seamlessly with engines and distribution infrastructure already established for fossil fuels. Such hydrocarbon biofuels are also referred to as “drop in” fuels, to differentiate them from ethanol and biodiesel (that may be blended with fossil fuels but require their own infrastructure and may have blend limits to ensure engine compatibility).
- There are also other chemicals that may be used as fuels, notably dimethyl ether (DME).

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[1] Advanced Biofuels Study: Strategic directions for Australia. Appendix, December 2011 http://www.arena.gov.au/_documents/abir/Advanced-Biofuels-Study-Appendix.pdf

16.2 Ethanol

Ethanol is a well defined, homogeneous chemical. It is a simple alcohol and the ethanol used as a transport fuel is chemically identical to the ethanol present in alcoholic beverages. Its use as a fuel began more than 100 years ago; for example the first Model T cars made by Ford were designed to operate on ethanol as an alternative to petrol.

Anhydrous ethanol (containing negligible amounts of water) is readily blended with petrol. Most such blends in Australia are up to ten percent (E10), although blends up to 85% (E85) have recently become available for vehicles with suitably designed engines. E85 is used more widely in Brazil and North America. There is no current Standard for ethanol fuel in Australia.

Ethanol is made via fermentation or by chemical processing. Numerous feedstocks are already in commercial use and many more feedstocks and processing pathways are at the pre-commercial stage. These are described in more detail in Chapter 17.

16.3 Biodiesel

Biodiesel is a generic name for fuels manufactured from vegetable oils or animal fats, via a process known as transesterification. Biodiesel feedstocks can range from refined oils, such as soybean and canola oil, to yellow greases (used cooking oils) and animal fats and even potentially grease trap and sewage grease.

Transesterification is a chemical process in which the oil and/or fat feedstock (called “triglycerides”) are chemically reacted with a mono-alcohol (usually methanol) and a base catalyst (usually sodium or potassium hydroxide). The feedstock is generally filtered and pre-processed before conversion to biodiesel, to remove contaminants and any water present. If the feedstock contains any free fatty acids, these can be removed or transformed into biodiesel using pre-treatment technologies.

When methanol is used then the transesterification process is described by the equation.

$$\mathbf{C_3H_5(OOCR)_3 + 3CH_3OH \quad -> \quad 3RCOOCH_3 + C_3H_5(OH)_3}$$

$$\text{(Triglyceride)} \quad \text{(Methanol)} \qquad \text{(Methylester)} \quad \text{(Glycerine)}$$

This produces a fuel that is commonly known as biodiesel or Fatty Acid Methyl Esters (FAME), with very similar combustion properties to petroleum diesel, but with lower viscosity. Biodiesel can be used ‘neat’ as a fuel designated as B100, or can be blended with petroleum diesel in any proportion. A common blend is B5, which consists of 5 units of biodiesel by volume to 95 units of petroleum diesel. Blends up to B20 are sold at many locations in Australia.

There are differences between various plant and animal derived fats and oils, due to the structural variations of the various fatty acids present. In most fats, the length of the fatty acid carbon chain ranges between sixteen and eighteen carbon molecules (C16 and C18). There are also differences in the degree of saturation (number and position of double bonds). Saturation is a major factor determining the physical properties of fats. Highly unsaturated vegetable oils are low viscosity liquids, while fully saturated animal fats are solid at ambient temperature.

Biodiesel properties vary with fatty acid composition of the feedstock(s), and are also influenced by the presence of minor compounds such as sterols, antioxidants and phosphatides. Fatty acid composition, however, has most impact on the freezing point, oxidative stability, cetane number and NOx emissions of biodiesel. The impact of the level of fatty acids is summarised in Figure 16-1 below.

Fatty acid:	Saturated	Mono-unsaturated	Poly-unsaturated
Cetane Number	High	Medium	Low
Cloud Point	High	Medium	Low
Stability	High	Medium	Low
NOx Emissions	Reduction	Medium Increase	Large increase

Figure 16-1 Biomass oil composition and impact on fuel properties

Another variable for biodiesel performance is the chain length of the fatty acids. Generally, the shorter the chain length, the higher the oxygen content (improved combustion and lower emissions). However, shorter chain length also lowers the energy content of the fuel, the Cold Filter Plugging Point (CFPP, gives improved winter operability) and the boiling point (reduced hydrocarbon and particulate emissions). The manufacture of compliant biodiesel can be achieved by blending various vegetable oils.

Low temperatures can cloud and even coagulate any kind of diesel fuel, and this applies particularly to biodiesel. Various types of feedstocks (e.g. tallow, palm oil) tend to elevate the CFPP, requiring formulations for winter or alpine use which restrict use of certain feedstocks or the addition of winterising additives.

Pure biodiesel is designated as B100 (i.e. 100 percent biodiesel), while a common blend, B20, consists of 20 percent biodiesel and 80 percent petroleum diesel. Low biodiesel blends (e.g. B5), would be expected to meet the Australian Standard for diesel (and the biodiesel would need to meet the Australian Biodiesel Standard – see Table 16-1 below).

Biodiesel acts as a mild solvent, and at high blends (>B20) it may clean out sediments that have previously built up in the fuel system. Thus users of high blends may need to replace fuel filters when converting to biodiesel usage. B100 is not compatible with certain types of elastomers and natural rubber compounds may degrade over time. However, with the trend towards lower-sulphur diesel fuel, many vehicle manufacturers have constructed engines with gaskets and seals that are generally biodiesel-resistant.

As biodiesel ages (remains unused in an idle vehicle or tank), it can degrade and form deposits that may damage fuel injection systems. Therefore, depending on blend levels and usage patterns of the vehicle, special considerations may be necessary for long-term operation on biodiesel. In general, the higher the blend level, the more potential for degradation. In particular, the use of B100 may require rubber hoses, seals and gaskets to be replaced with resistant materials, other non-rubber seals or biodiesel-compatible elastomers.

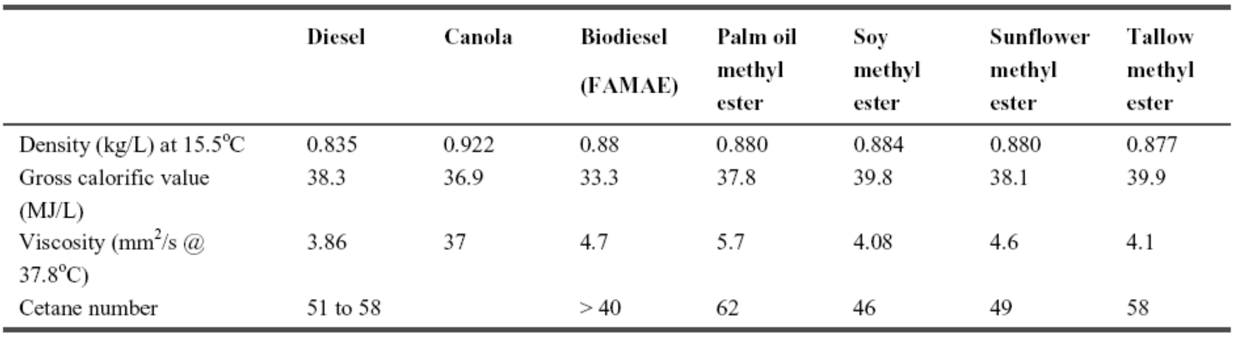
As noted above, biodiesel blends improve lubricity. This reduces engine wear. In addition, although biodiesel contains only about 90 percent of the energy content of diesel, its higher burning efficiency (due to higher cetane number) and better lubricity can result in an ‘effective’ energy content which is just a few percentage points below diesel.

Table 16-2 compares some of the physical and chemical properties of diesel, canola oil and methyl esters.

Table 16-1 Fuel standard parameters for biodiesel in Australia

Substance or property	Specification or amount	Unit
Sulphur	≤ 10	mg/kg
Sulphated ash	≤ 0.020	percent mass
Carbon residue – 10% distillation residue; or	≤ 0.30	percent mass
Carbon residue – 100% distillation sample	≤ 0.050	percent mass
Phosphorus	≤ 10	mg/kg
Free glycerol	≤ 0.020	percent mass
Total glycerol	≤ 0.250	percent mass
Metals – group I (Na, K)	≤ 5	mg/kg
Metals – group II (Ca, Mg)	≤ 5	mg/kg
Methanol content	≤ 0.20	percent mass
Density at 15°C	860 – 890	kg/m^3
Distillation T90	≤ 360	°C
Viscosity at 40°C	3.5 – 5.0	mm^2/s
Flashpoint	≥ 120.0	°C
Copper strip corrosion (3 hours @50°C)		
(a) biodiesel containing no more than 10 mg/kg of sulphur	≤ Class 1	
(b) biodiesel containing more than 10 mg/kg of sulphur	≤ No. 3	
Ester content	≥ 96.5	percent mass
Acid value	≤ 0.80	mg KOH/g
Total contamination	≤ 24	mg/kg
Cetane number	≥ 51.0	
Oxidation stability @110°C	≥ 6	hours

Table 16-2 Typical properties of diesel, canola oil, commercial US biodiesel, and various methyl esters



	Diesel	Canola	Biodiesel (FAMAE)	Palm oil methyl ester	Soy methyl ester	Sunflower methyl ester	Tallow methyl ester
Density (kg/L) at 15.5°C	0.835	0.922	0.88	0.880	0.884	0.880	0.877
Gross calorific value (MJ/L)	38.3	36.9	33.3	37.8	39.8	38.1	39.9
Viscosity (mm^2/s @ 37.8°C)	3.86	37	4.7	5.7	4.08	4.6	4.1
Cetane number	51 to 58		> 40	62	46	49	58

Table 16-3 provides a further comparison between biodiesel and low sulphur diesel, highlighting biodiesel's good cetane number (measure of smooth running), lubricity (previously provided by high sulphur in diesel, but this is out of favour due to the formation of acid rain from high sulphur fossil fuels), biodegradability and lower toxicity. Biodiesel's higher flash point provides a higher safety margin.

Table 16-3 Biodiesel/diesel property comparison[2]

	Biodiesel	Low-sulphur diesel
Cetane number	51-62	44-49
Lubricity	+	very low
Biodegradability	+	-
Toxicity	+	-
Oxygen content	up to 11%	very low
Aromatics	0	18-22%
Sulphur	0	0-350 ppm[3]
Cloud point	-	+
Flash point	150-205°C	51°C
Effect on natural, butyl rubber	can degrade	no impact

16.3.1 Renewable diesel

Renewable diesel, also known as green diesel and Hydro-treated Vegetable Oil (HVO), is made from the same oils and fats that are used to make biodiesel. However, instead of transesterification, the feeds are processed via processes known as hydro-treating and isomerisation. The resulting liquids are hydrocarbons rather than the fatty acid methyl esters (FAME) of biodiesel. Renewable diesel thus corresponds far more closely to conventional diesel fuels than does biodiesel. Neste Oil manufactures renewable diesel under the name NExBTL[4] and notes that it is of such high quality that it can be blended with lower quality fossil fuels and the blended product will still meet relevant quality standards.

16.4 Biomass-derived hydrocarbons

The renewable diesel described above has characteristics that are not available in either ethanol or biodiesel. Instead of being an alcohol or an ester, this biofuel is a hydrocarbon like petrol and diesel. The use of ethanol and biodiesel can be limited by blending and engine compatibility issues. However if the biofuel is a hydrocarbon that is fully compatible with existing fossil fuels it may be capable of much greater use. Such biofuels are also called "drop in" fuels because of their ability to readily replace or blend with fossil fuels. Their compatibility with fossil fuels offers benefits across the whole supply chain including storage, distribution and blending as well as final use by customers.

In addition to the renewable diesel pathway for fats and oils, drop in hydrocarbon biofuels can be made from biomass. A number of different technologies are being commercialised to achieve this. Typically these technologies first create an intermediate liquid, often referred to as "bio crude". The nature and composition of the bio crude will depend in part on the processing steps used in its manufacture. These intermediate liquids may be further upgraded to transport fuels in existing oil refineries or in stand-alone facilities.

Different processing pathways to make drop in hydrocarbons from biomass are described later in this report and include the following:

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[2] Biofuels for Transport, IEA, c 2004.
[3] Ultra-low sulphur diesel has less than 50 ppm and the level is being reduced to below 10ppm.
[4] http://www.nesteoil.com/default.asp?path=1,41,11991,12243,12335

The Fischer Tropsch process can convert gasified biomass (syngas) into a synthetic diesel fuel and naphtha (a liquid precursor to petrol) by building polymer chains out of the basic chemicals in the syngas. Other chemicals are also produced.

Fast pyrolysis of biomass creates a liquid called pyrolysis oil or bio-oil. While this liquid may be used as a fuel in boilers, furnaces and even gas turbines, it is not well suited to use in engines. Several groups are developing methods by which pyrolysis (with or without catalysts) and upgrading (with catalysts) may be combined to produce high quality transportation fuels.

Hydrothermal processing is another pathway for advanced biofuels, using a catalytic hydrothermal reactor. The process uses sub- and supercritical water to convert biomass to bio-crude, which is reported to have an oxygen content of less than 8% and a hydrogen content up to ten percent[5]. The intention is to upgrade this bio-crude to transport fuels in conventional oil refineries, so that the final product should be part of the overall fuel stream from the refinery and indistinguishable from conventional fossil fuels.

16.5 Other biofuels from biomass

Methanol is a simple alcohol. While ethanol has two carbon atoms, methanol has only one. Methanol's fuel properties have been known for many years but it is somewhat out of favour as a transportation fuel due to its low energy content and high toxicity. Its use might increase if fuel cell vehicles are developed with on-board reforming of hydrogen (methanol is an excellent hydrogen carrier).

Syngas from biomass gasifiers can be converted to methanol[6], however there is no commercial production at present. Methanol is currently made from natural gas and from the gasification of coal although, unlike sustainably grown biomass, these are not renewable feedstocks. Low level blends of methanol in petrol have been used in some European countries[7] and China has reported an ambitious program to make fuel methanol from coal[8].

Dimethyl ether (DME) can be produced from syngas in a manner similar to methanol production. It is a promising fuel for diesel engines, due to its good combustion and emission properties. DME has no carbon-to-carbon bonds, and as such soot production is miniscule. However it requires special fuel handling and storage equipment and some modifications of diesel engines. (Commercial production of DME is currently based on fossil fuel feedstock and the DME is used in the chemicals industry.)

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[5] Bioenergy Australia 2010 conference presentation, Thomas Maschmeyer.

[6] http://energyfuturesconference.com.au/userDocs/Presentations%202009/Barney%20Foran.pdf

[7] http://www.methanol.org/Methanol-Basics/Resources/Methanol-Fuel-Blending-Q-A.aspx

[8] http://www.ensec.org/index.php?option=com_content&view=article&id=148:chinatakesgoldinmethanolfuel&catid=82:asia&Itemid=324

16.6 Summary of fuel characteristics

Table 16-4 provides a comparison of some major fuel parameters for several fossil and biofuels.

Table 16-4 Fossil and biofuel characteristics[9]

Resources	Density (kg/m^3)	Heating Value ($GJ_{LHV}/tonne_{wet}$)	Heating Value ($GJ_{HHV}/tonne_{dry}$)	Octane (R+M)/2	Cetane
Crude Oil	845	42.7	45.4		
Fossil Derived					
Gasoline (petrol)	740-750	43.2 - 43.7	47.3	90 -100	5 - 20
Diesel	810-860	41.9 - 43.1	45.2	n/a	40 - 55
Light Fuel Oil No. 2	845	43.9	46.9		
Heavy Fuel Oil No. 6	1013	40.0	42.1		
LPG	525	46.1	48.0	102	
Methane	0.658 (gas)	50.1	55.5		
Biofuels					
Ethanol	791	26.4	29.8	100	8
Methanol	791	19.8	22.9	101	5
Hydrogen	70.8 (liquid) 0.0848 (gas)	120	143	97	
FT Diesel	770	42.9	46.4		
Rapeseed Oil	910-922	37.0	39.4	n/a	40 - 51
Biodiesel RME	880-920	37.3	39.8	n/a	51 - 58
Pyrolysis oil	1110 -1250	15.3	22.7	n/a	-
HTU[10] bio-crude		30 - 35	33 - 38		
HTU diesel		44.4	47		
DME[11]	665 (liquid)	28.2	29.8	n/a	55 - 60
DMM[12]	867	23.4	25.5	n/a	24
MTBE	746	34.8	37.6	120+	n/a
ETBE	745	36.2	39.0	120+	n/a

16.7 Biofuels in Australia

16.7.1 Summary

Ethanol and biodiesel are both produced commercially in Australia at present, the former from molasses and starch and the latter primarily from tallow and used cooking oil. Current production represents less than 2% of the more than 38 billion litres of ground transport fuels (petrol and diesel) used in Australia each year. At present there are no other biofuels made commercially in Australia from technologies that use lignocellulosic or algal feedstocks.

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[9] Source: Outlook for Advanced Biofuels, Carlo Hamelinck, University of Utrecht, The Netherlands, 2004.
[10] Hydrothermal upgraded
[11] Dimethyl ether – some physical properties similar to LPG
[12] Dimethoxymethane

National schemes exist to support the commercial production of biofuels. At the state level, New South Wales has legislated mandatory biofuel targets.

Biofuels R&D is quite active in Australia, with a number of pilot plants under construction or already built. Financial support has been provided via several funding programs established by the Australian government.

16.7.2 Commercial production

The installed annual capacity for biofuels in Australia in 2012 is reported by the Biofuels Association of Australia as follows:

- Ethanol capacity is 440 ML/year nationally, from two plants in Queensland and one in NSW [13].
- Installed biodiesel capacity at the start of 2012 was 200 ML/year, based on seven plants around the country[14]. These plants are designed to process a variety of feeds, with the plants currently in production processing mainly tallow and used cooking oil. A new plant, designed to produce 288 ML/year from a feed of soybeans, was announced in 2009[15] and groundbreaking for construction of the plant occurred in April 2012[16].

By comparison, the annual consumption of petrol and diesel and turbine (jet) fuel for transport in Australia is summarised as in Table 16-5 below[17]:

Table 16-5 Annual consumption of transport fuel in Australia

Transport fuel	Year 2009/10 (ML)	Year 2005/06 (ML)	Change over five years
Petrol	18,644	19,048	Down, by 2%
Diesel	19,044	15,804	Up, by 21%
Turbine fuel	6,675	5,359	Up, by 25%
Total	44,363	40,211	Up, by 10%

So the installed capacity for ethanol and biodiesel at the start of 2012 represents slightly less than 2% of the transport fuel consumed nationally.

16.7.3 Government biofuel programs

(i) Support for commercial production

Several schemes are operated by the Australian Government to assist the production of biofuels:

- The Ethanol Production Grants Program[18] is administered by the Department of Resources, Energy & Tourism. It aims to encourage the use of biofuels in the Australian transport industry. Grants are payable to ethanol producers at a rate of 38.143 cents per litre for eligible ethanol. The program was introduced in 2002, and in 2011 its operation was extended through to 2021.

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[13] http://www.biofuelsassociation.com.au/images/stories/pdf/ethanolmap.pdf
[14] http://www.biofuelsassociation.com.au/images/stories/pdf/biodieselmap.pdf
[15] http://www.abc.net.au/news/2009-05-19/port-kembla-to-get-biodiesel-facility/1686986
[16] http://www.natbiogroup.com/default.asp?id=77
[17] http://www.ret.gov.au/energy/Documents/facts-stats-pubs/Energy-in-Australia-2011.pdf
[18] http://www.ret.gov.au/resources/resources_programs/alternative_fuels_programs/ethanol_and_biodiesel_production/Pages/EthanolProductionGrant.aspx

- The Cleaner Fuels Grants Scheme[19] is administered by the Australian Taxation Office. It encourages the manufacture or importation of fuels that have a reduced impact on the environment. Cleaner fuels that meet the relevant fuel standard under the Fuel Quality Standards Act 2000 may be entitled to a cleaner fuel grant. It currently includes renewable fuels, such as biodiesel and renewable diesel. The current cleaner fuel grant is 38.143 cents per litre for eligible fuels and from 1 July 2011 this scheme has been extended indefinitely.

- The Clean Energy Future does not place a carbon price on domestic or light commercial vehicles[20]. A carbon price may be applied to heavy road transport in future.

(ii) Support for research and development

The Australian Government is supporting the development of 'second generation biofuels' via its Gen 2 grant program[21]. Successful applicants are conducting R&D for a range of fuels and supporting technologies under this program.

The Australian Biofuels Research Institute (ABRI) was established by the Australian Centre for Renewable Energy (ACRE)[22] to progress the commercialisation of advanced biofuels in Australia. ABRI has already allocated funds to James Cook University at Townsville for an algal biofuels project. Further funds have been allocated to the Advanced Biofuels Investment Readiness Program, which announced a call for funding applications in February 2012[23].

The Australian Government has a number of other funding programs, underway or in formation, that can be of benefit to biofuels research, development and commercialisation. These include the Clean Energy Finance Corporation, the Renewable Energy Venture Capital Fund and the Emerging Renewables Program.

The Australian Government has also established the Australian Renewable Energy Agency (ARENA)[24]. Legislation establishing ARENA as an independent statutory authority was made into law on the 4 December 2011 and ARENA commenced operations on 1 July 2012. It takes take over responsibility for a number of government programs including those administered by ACRE.

AusBiotech has managed the NCRIS Biofuels program[25] on behalf of the Australian Government. This program provided subsidised access to laboratory equipment and two pilot plants. The pilot plants are algae photobioreactors and raceway ponds in Adelaide, and a biorefinery in Mackay, Queensland.

The Rural Industries R&D Corporation (RIRDC) has recently led an examination of the nature of bioenergy R&D support in Australia[26] with a view to greater coordination and focus in this sector by the many government agencies that are involved.

(iii) State government mandates

At the state level, existing and proposed mandates provide support to the biofuels industry:

- New South Wales currently has a 6% ethanol mandate in total petrol sales[27]. This mandate does not apply to premium grades of petrol. A 2% biodiesel mandate commenced from 1st January 2010, and this is expected to increase to 5% when there is sufficient local biodiesel production to meet the mandate.

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[19] http://www.ato.gov.au/businesses/content.asp?doc=/content/00128216.htm&page=3&H3=&pc=001/003/044/008/006&mnu=9955&mfp=001/003&st=&cy=1
[20] http://www.cleanenergyfuture.gov.au/wp-content/uploads/2011/11/fact-sheet-16-transport-fuels-2-PDF.pdf
[21] http://www.ret.gov.au/energy/clean/gen2/Pages/gen2.aspx
[22] http://www.ret.gov.au/energy/clean/acre/Pages/default.aspx
[23] http://www.ret.gov.au/energy/clean/acre/abir/Pages/abirp.aspx
[24] http://www.ret.gov.au/energy/clean/arena/Pages/arena.aspx
[25] www.ncrisbiofuels.org
[26] https://rirdc.infoservices.com.au/items/10-078
[27] http://www.biofuels.nsw.gov.au

- Plans to introduce a 5% ethanol mandate into Queensland were suspended in 2010[28].
- Victoria carried out a biofuel review some years ago and a final report was tabled in February 2008[29]. The report recommended against the introduction of a mandatory biofuel target for the state. A number of recommendations were made for voluntary use of biofuels, together with a recommendation that that the situation be reviewed before 2013.
- Western Australia conducted a review of biofuels that culminated in a report issued in April 2007[30]. This report recommended a target of 5% biofuels by 2010 followed by a mandate for 5% biofuels by 2011 if the target was not met. This recommendation has not been implemented.

(iv) Recent Australian reports

Numerous reports on biofuels have been produced in Australia in recent years. These include:

- Advanced Biofuels Study – Strategic Directions for Australia (2011)[1]
- Flight path to Sustainable Aviation (2011)[31]
- Possible Futures: Scenario Modelling of Australian Alternative Transport Fuels to 2050 (2011)[32]
- Australian Biofuels 2011-12[33]
- Fuel For Thought (2008)[34]
- Demonstration of Market Delivery of Biodiesel from Indian Mustard in North-West NSW (2012)[35]
- Eucalypts for Biofuel Production in Northern Australia: Identifying species from current and future testing programs (2011)[36]
- Evaluating Biodiesel Potential of Australian Native and Naturalised Plant Species (2010)[37]
- Commercial Potential of Giant Reed for Pulp, Paper and Biofuel Production (2010)[38]
- Feasibility of Agave as a Feedstock for Biofuel Production in Australia (2010)[39]
- Future Biofuels for Australia - Issues and Opportunities for Conversion of Second Generation Lignocellulosics (2008)[40]
- Biofuels for Transport: A Roadmap for Development in Australia (2008)[41]
- Biofuels in Australia: Current Issues and Prospects (2007)[42]
- Biodiesel Production for Rural Australia: An Initial Concept and Model (2007)[43]

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[28] http://www.cabinet.qld.gov.au/MMS/StatementDisplaySingle.aspx?id=72283

[29] http://www.parliament.vic.gov.au/edic/inquiries/biofuels/final_report.html

[30] http://www.agric.wa.gov.au/objtwr/imported_assets/content/sust/biofuel/biofuelstaskforcereportapr07.pdf

[31] http://www.csiro.au/en/Outcomes/Energy/Powering-Transport/sustainable-aviation-fuel-report.aspx

[32] http://www.ret.gov.au/resources/Documents/transport_fuels/ScenarioModellingAustralianAlternativeTransportFuels2050.pdf

[33] Available for purchase from Ecco Consulting, http://www.eccoaustralia.com/services.php?id=1

[34] http://www.csiro.au/files/files/plm4.pdf

[35] https://rirdc.infoservices.com.au/items/11-153

[36] https://rirdc.infoservices.com.au/items/11-064

[37] https://rirdc.infoservices.com.au/items/10-216

[38] https://rirdc.infoservices.com.au/items/10-215

[39] https://rirdc.infoservices.com.au/items/10-104

[40] https://rirdc.infoservices.com.au/items/08-117

[41] Biofuels for Transport: A Roadmap for Development in Australia. Report by M Thomas and J Wright for the Australian Academy of Technological Sciences and Engineering, 2008

[42] https://rirdc.infoservices.com.au/items/07-071

[43] https://rirdc.infoservices.com.au/items/07-140

17. Production of ethanol and biodiesel

17.1 Summary

17.1.1 Ethanol

Ethanol may be blended with petrol and used as a renewable transport fuel. Current ethanol manufacture around the world is based on the fermentation of sugar that is derived either from sugar cane or from a variety of starch-producing crops such as corn, wheat and cassava. The two largest ethanol producing countries in the world are the United States and Brazil, where extended, large scale government support has underpinned the development of ethanol fuel industries based on corn and sugar cane respectively. In Australia ethanol has been made for many years from low value molasses and waste starch. From 2009 it has also been made in Queensland in an integrated facility using grain sorghum as feed.

It is also technically feasible to make ethanol from lignocellulosic materials such as wood and agricultural residues.

- Lignocellulosic biomass contains significant quantities of six carbon and five carbon sugars that may be fermented to produce ethanol, provided these sugars are first “released” from their polymeric structure in the biomass and made available for fermentation.
- It is also possible to break the wood into small molecules (“syngas”) via gasification, and then rebuild those molecules into ethanol via chemical synthesis or fermentation.

These different biomass-to-ethanol technologies have been broadly understood for many years but have not yet moved past the pilot and demonstration stage. This is expected to change over the next few years however, with several commercial scale biomass-to-ethanol plants being built overseas. Recent and current investments in new biomass to ethanol technologies overseas are measured in hundreds of millions of dollars. If these initial commercial plants are successful, it will then be possible to engage with companies offering proven biomass to ethanol technology at commercial scale for the construction and operation of biomass to ethanol plants in Australia.

In addition to reliable and competitive technology, commercial biomass to ethanol plants need reliable and competitive feed and markets. A biomass to ethanol plant designed to produce 200 Ml/year of ethanol is expected to use approximately one million tonnes of green biomass each year.

In the absence of any commercial scale plants there is no proven data on the cost of second generation ethanol, however a number of US organisations active in the field indicate that they expect to be able to make ethanol that is competitive with fossil fuels.

17.1.2 Biodiesel

Biodiesel is a diesel-compatible fuel that can be produced from a variety of vegetable oils and animal fats. Biodiesel may be used as a complete replacement for mineral diesel made from crude oil, but is more often used in blends with this diesel. The most common method of production is a process called transesterification, which is widely utilised in commercial plants in Australia and the rest of the world.

Proven feedstocks for biodiesel manufacture include waste cooking oils, tallow, and oil from oilseeds such as canola, oil palm and many other oil producing plants. These feedstocks have all varied considerably in price over the past five years and a decision as to whether a given feedstock will be used for biodiesel manufacture must include consideration of feedstock cost and whether there are subsidies for biodiesel production that make the business commercially viable. Several biodiesel plants built in Australia over the past five years have closed down because of increases to feedstock prices.

Biodiesel production in Australia at present is largely focussed on the lower value feedstocks – tallow and used cooking oil, which allow profitable operation of processing facilities.

Use of some feedstocks may also be influenced by the environmental image of the material, such as palm oil sourced from South East Asian plantations planted on environmentally sensitive land (e.g. cleared rainforest or peat lands).

17.2 First generation ethanol

First generation biofuel facilities produce ethanol via the fermentation of sugars by yeast, a process that is fundamentally the same as production of alcoholic beverages such as beer and wine. Fermentation produces a dilute stream of ethanol, which must then be concentrated to be used as a fuel. This concentration can be achieved via distillation and molecular sieves.

The sugars used for fermentation may come from a variety of crops and processes. They are generally sourced from food-related crops, either via low-value residues following extraction of most of the sugar and starch, or from higher value (and higher quality) materials that may be used for ethanol in competition with other, food-related uses.

(i) Sugar

When sugar cane is processed in Australian sugar mills it is first crushed to release the sugar juice from the cane. The cane fibre is called bagasse and is commonly used as fuel for heat and power generation. The juice is processed to recover as much of the sugar it contains as is economically possible, to make crystal sugar for human consumption. The residual material from the sugar extraction process is called C-molasses and it still contains some sugar that cannot be recovered economically. In Australia C-molasses is used as feedstock for ethanol fermentation, and also as cattle feed.

The very large sugar industry in Brazil has set up on a different basis to Australia, with the cane juice able to be used for either crystal sugar production or ethanol production according to the prevailing market prices (both are used domestically and also exported).

(ii) Starch

In Australia and other parts of the world starch is also used as a feedstock for ethanol manufacture. Starch is a polymer (long chain) of sugar molecules and for many years enzymes have been commercially available to break down ("hydrolyse") the starch polymers, releasing sugar molecules. This process is called saccharification. These sugars may then be fermented by conventional yeasts. Different starch feeds are used in different countries. For example:

- Australia – for some years the Manildra group in NSW has made ethanol from low value starch produced in a wheat processing facility[1] and by-products from the ethanol process are used to produce livestock feed. In Queensland, an ethanol facility near Dalby uses grain sorghum as feed. In addition to ethanol, the Dalby facility also produces distillers grain and high protein stock feed[2].
- United States – the USA has a very large ethanol industry that uses corn as feedstock. The starch from the corn is first saccharified, a process that uses enzymes to break the starch down into its component sugars. These sugars may then be fermented and the resulting ethanol distilled. In a similar fashion to the Dalby ethanol refinery in Queensland, the US corn processing yields a number of saleable products in addition to ethanol.
- Thailand – A significant source of starch in Thailand is cassava (or tapioca) and some of this starch is used to manufacture ethanol.

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[1] http://www.manildra.com.au/our_products/article/ethanol/
[2] http://www.dbrl.com.au/process.htm

(iii) Current production

Ethanol production statistics for the world are summarised in Table 17-1 below[3]:

Table 17-1 World ethanol production statistics

Country or region	Production in 2011 (million US Gallons)	Production in 2011 (million litres)
North and central America (excl Canada)	14,401.34	54,508
South America (excl Brazil)	5,771.90	21,843
Brazil	5,573.24	21,094
Europe	1,167.64	4,417
Asia (excl China)	889.70	3,368
China	554.76	2,100
Canada	462.30	1,750
Australia	87.20	330
Africa	38.31	145
Total	28,946.39	109,562

As can be seen from the table, the Americas are the major locations for production of ethanol in the world; together they accounted for almost 90% of ethanol production in 2011. Australia's production contributed approximately 0.3% to the world total.

(iv) Use of ethanol with diesel fuel

Ethanol mixed with diesel as a blended fuel is generally referred to as e-diesel. It is a blend of standard No. 2 diesel fuel containing up to 15% ethanol and a proprietary additive to maintain blend stability and certain fuel properties, which may comprise from 0.2% to 5.0% of the blend. The US government has investigated e-diesel[4] and highlighted concerns primarily with its flammability characteristics. E-diesel blends containing 10-15% ethanol have the vapour pressure and flammability limits of ethanol. E-diesel creates increased risks of fire and explosion over diesel and use of e-diesel blends should be accompanied by a number of actions to minimise these risks. These blends are considered experimental in the USA and are not used in Australia.

17.3 Ethanol via advanced generation processes

A number of alternative process pathways are available to turn lignocellulosic biomass into ethanol. They all have three main stages:

- Pre-treat the biomass to prepare it for further processing.
- Break the biomass down into components, via hydrolysis or via gasification.
- "Reform" those components into ethanol, via fermentation or catalytic synthesis.

The cellulose and hemicellulose in biomass are essentially long polymer chains of sugar molecules, which may be broken into the component sugar molecules via a process known as "hydrolysis". This process is complicated by the lignin in the biomass, which may be considered as the crystalline structure that binds the biomass together. In general terms, C6 or hexose sugars are associated with the cellulose and C5 (the molecule is composed of five carbon atoms) or pentose sugars are

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[3] http://ethanolrfa.org/pages/World-Fuel-Ethanol-Production

[4] Safety and performance assessments of ethanol/diesel blends (e-diesel), September 2003 – National Renewable Energy Laboratory publication no. NREL/SR – 540 - 34817

associated with the hemicellulose. Conventional yeasts can readily ferment C6 sugars, but the fermentation of pentose sugars to ethanol requires yeasts that are genetically adapted or different micro-organisms altogether.

In contrast to hydrolysis for sugars, gasification breaks biomass down into small, simple molecules such as carbon monoxide and hydrogen.

These processes have generally been demonstrated at the pilot scale, and demonstration at the commercial scale is expected over the next few years. Several different processing pathways, and projects that are underway or planned, are described below.

17.3.1 Acid hydrolysis

Acids can be used to hydrolyse cellulose and hemicellulose into their component sugars. Both dilute and concentrated acid hydrolysis have been under development for many years, and may be applied to more heterogeneous biomass, including municipal solid waste and urban green wastes. Being relatively well developed, there is perceived to be less scope for improvement to reduce costs and increase performance of acid hydrolysis when compared with other methods for hydrolysis. When dilute acid hydrolysis is applied, this tends to be in a single pass process, while concentrated acid hydrolysis invariably requires recovery and recycling of the acid for environmental and cost reasons.

Acid hydrolysis, which liberates the sugars, is followed by acid neutralisation or recovery, then fermentation of the sugars to ethanol and distillation to concentrate and recover the ethanol from the fermentation liquid.

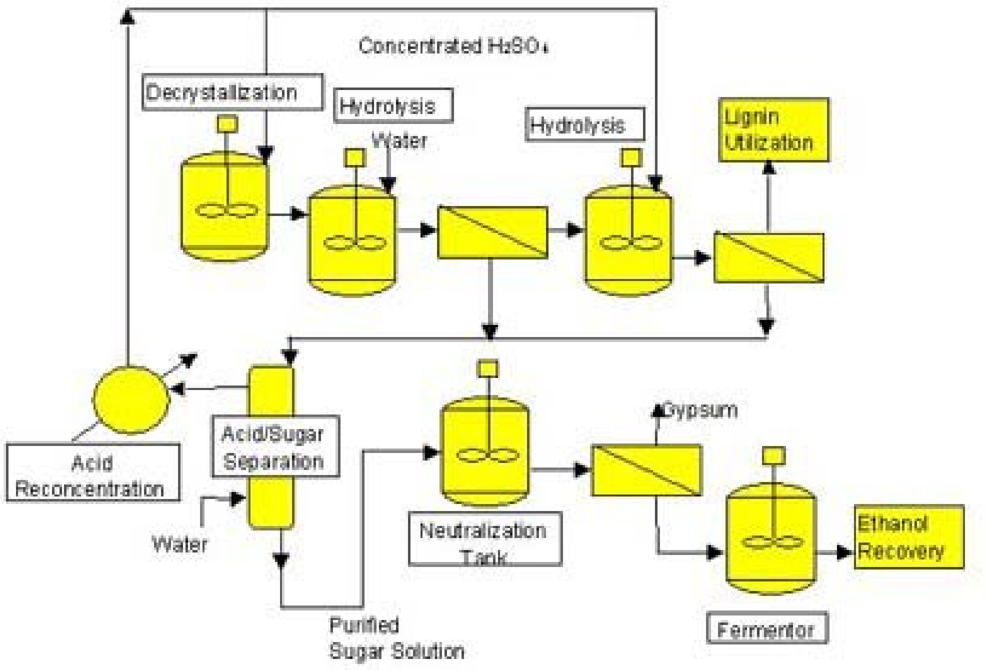

Figure 17-1 Biomass to ethanol using concentrated acid hydrolysis

One company that is commercialising this process is the US organisation BlueFire Renewables[5]. A demonstration unit has operated in Japan for some years and BlueFire has planned a commercial scale ethanol plant at Fulton, Mississippi. This plant will have an output of approximately 70 Ml of ethanol per year. Site preparation was completed in 2011 and construction appears to be on hold pending finalisation of funds.

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[5] http://bfreinc.com/

17.3.2 Enzyme hydrolysis

Hydrolysis can also be achieved using enzymes. The enzymes need to be specifically matched to the biomass feedstock and the biomass needs to be more homogeneous than for acid hydrolysis. In recent years there has been a dramatic fall in the cost of enzymes for this process, particularly following US government-funded development programs by major enzyme companies.

- Abengoa[6] already manufactures ethanol via first generation technology and is seeking to manufacture ethanol from biomass sugars via enzyme hydrolysis. The group has already built a biomass to ethanol demonstration plant near Salamanca in Spain. At June 2011 the plant had been operated for more than 6,000 hours and achieved yields of approximately 200 litres of ethanol per tonne of wheat straw. The target yield is 300 litres per tonne[7]. In 2011 Abengoa started construction of a commercial scale biomass to ethanol plant at Hogoton in Kansas, sized to produce approximately 90 ML of ethanol per year[8]. Funding has been supported by a US$134 M loan guarantee from the US Government.

- US company POET operates a number of first generation ethanol plants across the USA[9]. POET has already operated a biomass to ethanol pilot plant sized to make approximately 75,000 litres of ethanol per year. In early 2012 POET announced a joint venture with Royal DSM[10] and the start of construction on "Project Liberty", a 75 Ml per year biomass to ethanol plant at Emmetsburg in Iowa. The plant will use waste biomass from the corn industry and is scheduled for start up in 2013.

- Beta Renewables also uses the enzymatic hydrolysis pathway[11]. This company and a related company Chemtex are part of the Italian group Mossi & Ghisolfi (M&G). Beta Renewables has run a one tonne per day pilot plant in Italy since 2009 and a commercial scale plant at Crescentino in Italy is due for start up by the end of 2012. This plant is to process wheat straw and *Arundo donax* (a tall, perennial cane) through to approximately 50 ML per year of ethanol, with production then increasing to 75 ML per year. A second commercial plant, to be built in Brazil with GraalBio, was announced in May 2012[12]. Thirdly, in August 2012 Chemtex received a loan guarantee from the USDA for US $99 M to support funding of a proposed 75million litre/year plant to be built in the Sampson County of North Carolina, USA[13].

- In Canada, Iogen Energy (a joint venture between Iogen Corporation and Royal Dutch Shell) has operated a biomass to ethanol demonstration plant for some years[14]. This plant has processed a range of crop residues and also hardwood chips, producing up to 6,000 litres of ethanol per day. In 2009 Iogen Energy announced feasibility work towards a commercial scale plant at Prince Albert in Canada, but in 2012 announced that the project was on hold[15].

- Mascoma is a US corporation that has developed genetically modified yeasts capable of both hydrolysis and fermentation[16]. Mascoma has announced that in 2012 it will start construction of a 75 Ml per year biomass to ethanol plant in Kinross, Michigan. Proposed feed is hardwood. The plant is to be built so that its output may be increased at a later date. Total cost is estimated at US$232 M, which is partly supported by a grant of US$80 M from the US Department of Energy.

- Inbicon has built a demonstration plant in Kalundborg, Denmark to showcase its technology for enzymatic hydrolysis of straw, followed by fermentation to ethanol[17]. Commissioned in 2009, this

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[6] http://www.abengoa.com/corp/web/en/negocio/energia/biocombustibles/index.html
[7] http://esse-community.eu/articles/abengoa-tested-in-salamanca-its-bioethanol-plant-for-u-s
[8] http://www.bizjournals.com/wichita/news/2011/08/19/abengoa-cellulosic-ethanol-Hugoton.html?page=2
[9] http://www.poet.com/inspiration/index.asp
[10] http://www.dsm.com/en_US/cworld/public/markets-products/pages/energy.jsp
[11] http://www.betarenewables.com/index.html
[12] http://graalbio.com/graalbio/wp-content/uploads/2012/02/First_cellulosic-ethanol_plant.pdf
[13] http://www.betarenewables.com/USDA-Loan-Guarantee-R4-08-22-12.pdf
[14] http://www.iogen.ca/company/demo_plant/index.html
[15] http://www.iogen.ca/news_events/press_releases/2012_04_30_refocus.pdf
[16] http://www.mascoma.com/pages/index.php
[17] http://www.inbicon.com/Projects/Kalundborg%20Demonstration%20plant/Pages/Kalundborg%20Demonstration%20plant.aspx

plant is designed to produce more than 5 ML of ethanol per year, and also provide lignin for use as renewable fuel in an adjacent coal-fired power station owned by its parent company DONG Energy.

- China National Cereals, Oil and Foodstuffs Import and Export Corporation (COFCO) is the nation's largest grain trader. In 2011 COFCO announced the development of a commercial scale (63 Ml/year) biomass to ethanol plant, following operation of a pilot plant during the period 2007 to 2011[18].

- Also in China, Henan Tianguan Fuel Ethanol Co. Ltd announced in 2011 that it would build several commercial straw to ethanol plants from 2011 onwards, with a target of 150 Ml/year of ethanol production capacity by 2014[19]. The company has operated a 13 Ml/year demonstration plant since 2009.

17.3.3 Gasification and reforming

Synthesis gas from the thermal gasification of biomass contains hydrogen and carbon monoxide, which can be further processed with catalysts to produce ethanol. One advantage of this pathway, compared with enzymatic hydrolysis, is that the gasification process is not as dependent upon the cellular structure of the biomass, which allows a wide variety of feedstocks to be considered. The catalytic synthesis process eliminates the need for micro-organisms to produce the ethanol, which is instead produced via chemical processing.

- Enerkem is a Canadian company that uses gasification and catalytic synthesis to make ethanol and methanol from a variety of feeds, including biomass and also municipal solid waste (MSW). Enerkem finished construction of a demonstration unit in 2009 (output 5 Ml/y from dry waste wood). The company has begun construction of a 38 Ml/y plant in Edmonton Canada, which will use approximately 90,000 dry tonnes per year of sorted MSW as feed. This plant is due for start up early 2013[20]. Enerkem is also arranging funding for similar-sized plants in Mississippi, USA and Quebec, Canada, again using MSW as feed.

- Fulcrum BioEnergy also uses a gasification/synthesis pathway to make ethanol. Its pilot plant commenced operation in 2009 and it has recently commenced construction of a 40 Ml/y ethanol plant in Nevada[21]. Commercial operations are expected to commence in the second half of 2013. The plant is reported as costing US $180 M and requiring 147,000 tons of municipal waste per year as feed.

- Range Fuels proposed the use of gasification followed by synthesis to methanol and then ethanol. The company built a commercial scale plant at Soperton in Georgia several years ago, however Range Fuels filed for bankruptcy before the plant operated commercially. In early 2012 the plant and site were sold to LanzaTech, another biofuels company[22].

17.3.4 Gasification and fermentation

As an alternative to the use of industrial catalysts to convert synthesis gas to ethanol, a number of organisations have developed processes to carry out this step using microorganisms that ferment carbon monoxide and hydrogen gases. Some companies refer to these microorganisms as "biocatalysts"[23].

- US company Coskata[24] has developed such a process and has built a pilot scale facility in Pennsylvania, which was started in October 2009 and is sized to produce approximately 150,000 litres per year of ethanol. Coskata has formed an association with General Motors and in 2010 it

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[18] http://www.biofuelsjournal.com/info/bf_articles.html?ID=113932
[19] http://www.biofuelsjournal.com/info/bf_articles.html?ID=115455
[20] http://enerkem.com/en/facilities/plants/edmonton-alberta-canada.html
[21] http://www.biofuelsdigest.com/bdigest/2011/11/21/waste-management-invests-in-fulcrum-provides-70m-debt-for-first-commercial-project
[22] http://biofuelsdigest.com/bdigest/2011/12/05/the-range-fuels-failure
[23] http://www.ineosbio.com/63-Biocatalyst.htm
[24] http://www.coskata.com/

signed a Memorandum of Understanding with the Victorian State Government to examine the feasibility of a plant to make ethanol from municipal waste in Melbourne[25]. The Coskata process is capable of using renewable biomass and also natural gas as feed. In July 2012 construction of a first commercial scale biomass facility in Alabama was put on indefinite hold and the company announced that it will focus on natural gas (rather than renewable biomass) as feedstock for the first few commercial plants[26].

- Ineos Bio uses gasification followed by bacterial fermentation to produce ethanol. Its process was developed by Bioengineering Resources Inc. In July 2012 Ineos Bio completed construction of a commercial plant at Vero Beach in Florida, which is due to begin operation later in 2012[27]. The plant is expected to use 150,000 ton/y of mixed biomass[28] for the manufacture of approximately 30 ML/year of ethanol and 6MW of electricity (approximately 4 MW will be used within the plant, leaving some 2MW for export). The capital cost for the plant is quoted at US $130 M, backed by $52.5 M in grants and a $75 M USDA loan guarantee[29].

- New Zealand company LanzaTech uses genetically modified microorganisms to convert syngas into ethanol. The company built a pilot plant in 2008 that was sized to produce approximately 60,000 litre/year of ethanol. A demonstration unit sized at 400,000 litre/year was built during 2011 in China with Baosteel Group Corp and the Chinese Academy of Sciences[30]. The gas to be used in the Chinese plant is generated during steel production, not from the gasification of biomass. The company is also interested in processing syngas from other feeds. In 2011 it announced collaboration on fuels from coal gasification with a Chinese group[31] and in early 2012 LanzaTech bought the inoperative Range Fuels biofuels plant in Soperton, Georgia, with the aim of utilising some of the existing equipment and local biomass supplies.

17.4 Feed quantities for ethanol plants

The amount of biomass required for a commercial scale ethanol plant is a function of the size of the plant, the efficiency of conversion of biomass to ethanol and other use of biomass on-site, for example energy supply.

The size of a commercial scale starch to ethanol plant (in the US corn industry) typically varies from 100 to 200 megalitre of ethanol output per year.

The US Government's National Renewable Energy Laboratory (NREL) has examined the yield of ethanol from biomass and has also estimated the projected cost of a full scale commercial plant. In its techno-economic report of May 2011[32] it examined a plant designed to process some 700,000 dry tonnes per of corn stover per year. If green wood at 50% moisture content is used as feed instead of corn stover this suggests a feed requirement of approximately 1.4 million tonnes per year. Ethanol yield is assumed to be 270 litre per dry tonne (79 US Gal/dry ton).

The commercial prototype plants under construction are generally sized to produce less than 200 Ml/year. It is not always clear whether these plants will be expanded in time or whether subsequent plants would be larger. Larger plants provide economies of scale but also require larger supplies of biomass throughout their operating life.

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[25] http://www.invest.vic.gov.au/230310VictoriasignsontobioethanolplantwithCoskata

[26] http://www.biofuelsdigest.com/bdigest/2012/07/20/coskata-switches-from-biomass-to-natural-gas-to-raise-100m-in-natgas-oriented-private-placement/

[27] http://www.ineosbio.com/77-News_coverage-49.htm

[28] http://www.tcpalm.com/news/2011/jun/21/indian-river-agrees-to-provide-55000-tons-waste

[29] http://www.ineosbio.com/76-Press_releases-18.htm

[30] http://www.lanzatech.com/sites/default/files/imce_uploads/lanzatech_demo_plant.pdf

[31] http://www.lanzatech.co.nz/sites/default/files/imce_uploads/lanzatech_in_coal_to_fuel_project_with_yankuang_group_nov_29_2011_fver2.pdf

[32] Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol. NREL/TP-5100-47764, May 2011

17.5 Biodiesel technology

Biodiesel is a fuel that may be used in blends with, or instead of, petroleum diesel. It is produced by chemically modifying vegetable oils or animal fats. It may be manufactured from a range of feedstocks, including waste cooking oils, oil seed oils such as canola, oil palm, and many other oil producing plants. Some of these plants and oils are also suitable for humans and animal use, whereas others are unsuitable for humans/animal use but may be used for biofuels.

The Australian Government's "Fuel Quality Standards Act 2000" defines biodiesel as "a diesel fuel obtained by esterification of oil derived from plants or animals". Some reports also use the term biodiesel for biofuels produced via gasification and Fischer Tropsch synthesis of woody feeds[33]. In this report the latter fuels are termed synthetic diesel or syndiesel, in keeping with many other reports and with the benefit of distinguishing between fuels that have fundamentally different feeds/production processes and product characteristics. See Chapter 18 below for synthetic diesel.

17.5.1 Transesterification

The most common process for production of biodiesel is called transesterification. This process converts the long chain fatty acids present in triglycerides (vegetable oils and animal fats) into molecules that have better properties for use as transport fuels. These fatty acids in oils and fats are also known as triglycerides, a name that refers to the tendency for three fatty acids to be joined together by single carbon-to-carbon bonds. Transesterification breaks these carbon-to-carbon bonds and each triglyceride molecule becomes three fatty ester molecules that can be used as biodiesel. The reaction requires an alcohol, usually methanol, and creates the by-product glycerol, generally as follows:

100 kg triglycerides plus 10 kg methanol -> 100 kg biodiesel plus 10kg glycerol[34]

In practice excess alcohol is used, in the presence of a base catalyst such as NaOH or KOH. Other methods exist, such as acid catalysed transesterification, however base catalyst transesterification is the most widely used process[35].

The composition of oils varies with source (e.g. tallow versus canola), both in terms of the chain length of the fatty acids and in the level of saturation of the fatty acids (i.e. the number of double carbon-to-carbon bonds present). This affects the characteristics of the biodiesel that is produced; for example the cloud point of biodiesel varies from feed to feed. For this reason it is not uncommon for biodiesels made from low cost and high cost feeds to be blended, with the latter used to improve the characteristics of the overall fuel.

17.6 Biodiesel feedstocks

Biodiesel can be made from a wide range of feedstocks. Major current and potential feedstocks are summarised in the ATSE report on biofuels from 2008[41] and include the following:

(i) Used cooking oil

Used cooking oil (UCO) is a well regarded feedstock for biodiesel manufacture, particularly as it was previously considered a waste product and is still available at prices that allow competitive manufacture of biodiesel. It is sourced from fast food outlets and other parts of the catering industry, and is a feedstock for all of the Australian biodiesel plants listed as "in production" in 2009[9]. Its availability is obviously determined by the quantities created as waste from cooking around the country.

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[33] Australia's future oil supply and alternative transport fuels. Final senate committee report to the Legislative and General Purpose Standing Committee, February 2007

[34] Biodiesel Production Technology. By J Van Gerpen etal for the US National Renewable Energy Laboratory Subcontractor Report no. SR 510-36244, July 2004

[35] http://www.biodiesel.org/pdf_files/fuelfactsheets/Production.PDF

(ii) Tallow

Tallow is rendered fat from the processing of animals, mainly sheep and cattle in Australia. Some high grade tallow is used for human consumption and lower grade tallow is used for animal feed, soap and chemical manufacture, as well as for biodiesel manufacture. It is noted as a feedstock for most of the biodiesel plants in production in Australia during 2009. As with UCO, the availability of tallow is limited by the size of the industry that produces it.

(iii) Oilseeds

Oilseed crops include canola and mustard. Existing crops are grown for human consumption but can also provide useful feedstock for biodiesel manufacture. A particular benefit of biodiesel made from canola oil is its low cloud point and it is sometimes used in blends with biodiesel made from tallow to provide a combined biofuel that has better characteristics at low temperatures.

Recent pricing for oil seeds as food crops has made them generally uneconomic for biodiesel production in Australia. They are still used for biodiesel production in Europe however, where financial incentives for biofuels are greater.

There is some interest in developing oil seed crops that can be grown on marginal land deemed unsuitable for food production. This approach appears to be still at the pre-commercial stage in Australia.

(iv) Palm oil

The oil palms grown in South East Asia have become a major source of feedstock for biodiesel in recent years. These palm trees are grown in plantations, particularly in Malaysia, Indonesia and Thailand. The palm fruit contains significant quantities of oil and the industry has grown considerably over recent years as use of the oil has expanded in food, chemical and biofuels markets. The growth of these markets has seen the price of palm oil increase significantly in recent years (see below). It has also seen the expansion of plantations and a number of environmental groups have campaigned against the industry after plantations were established at the expense of rainforest or on peat land in Indonesia with stores of carbon that could be released when the land is cleared and prepared for plantations. As such, palm oil has fallen out of favour in some European countries, particularly Germany. However it is still used extensively as a feedstock for fuel in SE Asia. Countries such as Thailand are struggling to meet their targets for biofuel adoption due to a lack of suitably priced palm oil.

(v) Soy

Oil from soybeans has been a major feedstock for biodiesel production in Europe and North America. Soybeans are grown particularly in the Americas and the soy meal left following oil extraction can be used as stock feed.

In Australia, the only major new biodiesel plant currently being built is based on soybeans. This plant at Port Kembla[36] intends processing 1.4 million tonnes of soybeans into 288 ML of biodiesel and more than 800,000 tonne of soybean meal each year.

(vi) Jatropha

Jatropha (*Jatropha curcas*) is a small tree or shrub that grows nuts rich in oil suitable for biodiesel manufacture. It is receiving considerable interest because it can be grown on low grade land and can fix nitrogen, potentially improving soil quality. It is being grown in India and other parts of Asia but not yet in Australia. In particular:

- It is declared a noxious weed in several states of Australia.
- Harvesting of the nuts is currently carried out manually, which is commercially viable in Asia but not in Australia

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[36] http://www.natbiogroup.com/default.asp?id=142

(vii) Pongamia

Pongamia (*Pongamia pinnata, Milletia pinnata*) is another tree crop that grows nuts rich in oil. Like jatropha it is a nitrogen fixer and can be grown on marginal land. Unlike jatropha it is not declared a noxious weed in Australia. It is not yet grown commercially in Australia however it is the subject of work by several groups including:

- University of Queensland – investigating its genetic structure with a view to producing trees that are more commercially attractive[37].
- Bioenergy Plantations Australia[38] and Australian Phytofuel[39], who are both seeking to develop commercial plantations in northern Australia.

A separate chapter of this report is devoted to analysis of the supply chain costs for a hypothetical pongamia plantation in northern Australia.

(viii) Algae

Algae is receiving considerable attention as a possible source of biofuel in the future. Algae can produce oils that are similar to oils from the feedstocks described above, and any commercial production would result in biodiesel similar to the fuel currently available. Algae is considered in more detail in Chapter 20.

17.7 Biodiesel industry status

(i) Australia

At the start of 2012 the installed annual biodiesel capacity in Australia was 500 ML, based on seven plants located around the country and designed to process a variety of feeds. At that time only four of the plants were in operation, producing 115 ML of biodiesel from tallow and used cooking oil[40]. By comparison, overall diesel consumption for transport in Australia was 19,044 ML for the year 2009/10[12].

(ii) International

The biodiesel industry is considerably larger in Europe than in Australia. Total installed capacity for the European Union (EU) was estimated to be 21 million tonnes per year in 2010, although production from that installed capacity was only 9 million tonnes[41].

In the United States, total biodiesel production in 2011 was reported as 1.1 billion US gallons (4.2 billion litres)[42]. By comparison, diesel consumption in the USA was estimated to be 35.6 billion US gallons for the year 2010[43].

17.8 Renewable diesel

An alternative process, known as hydro-refining or hydro-treating, may also be applied to animal and vegetable oils and fats. This process yields a biofuel with different characteristics to the biodiesel described above. The fuel made with this process is called green diesel[44] or renewable diesel[45] to differentiate it from biodiesel made via transesterification.

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[37] http://www.cilr.uq.edu.au/UserImages/File/factsheets/Pongamia%20Binder1.pdf
[38] http://www.bioenergyresearch.com.au/home/
[39] http://www.phytofuel.com.au/
[40] http://www.biofuelsassociation.com.au/images/stories/pdf/biodieselmap.pdf
[41] http://www.ufop.de/downloads/Auszug_Biodiesel_E_2011_web-1.pdf
[42] http://www.biodiesel.org/production/production-statistics
[43] http://www.eia.gov/renewable/afv/xls/New%20C2%20Native.xls
[44] http://www.uop.com/wp-content/uploads/2011/01/UOP-Hydrorefining-Green-Diesel-Tech-Paper.pdf
[45] http://www.nesteoil.com/default.asp?path=1,41,11991,12243,12335

Renewable diesel offers a number of useful attributes over biodiesel[46]. It is fully compatible with petroleum diesel. It has a higher cetane number and lower cloud point than petroleum diesel and biodiesel, and a higher energy density than biodiesel.

Renewable diesel is typically produced in a process that adds hydrogen to an oil or fat in the presence of a catalyst. Unsaturated bonds in the oil or fat are broken and the material is also deoxygenated. Process conditions may be varied to optimise the attributes of the renewable diesel being made, particularly if it is to be optimised for used in blends with petroleum diesel.

Finnish oil company Neste Oil has developed a process to hydro-treat vegetable and animal oils and fats to make a product called NExBTL diesel, which it claims is superior to both biodiesel and petroleum diesel. Neste has built a number of large commercial plants to manufacture this product[47]:

- Two plants in Finland commissioned in 2007 and 2009, each with capacity of 190,000 tonne per year of products
- A refinery in Singapore commissioned in 2011 with a capacity of 800,000 tonne/year
- A refinery in the Netherlands commissioned in 2011, also with capacity of 800,000 tonne/year

Brazilian oil company Petrobras has developed a process called H-BIO and has built facilities to make renewable diesel at four of its refineries[48].

UOP and the Italian oil company Eni have developed a process they call “ecofining” to make renewable diesel in an oil refinery environment. Eni and Portuguese oil company Galp Energia have licensed the technology but it is understood that no commercial facilities have been built yet.

In Australia, BP has modified the hydrogenation unit at its Bulwer Island refinery to accept animal fats and vegetable oils as feed to make renewable diesel[49].

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[46] http://petrofed.winwinhosting.net/upload/2_PNair02.pdf
[47] http://www.nesteoil.com/default.asp?path=1,41,11991,12243,12335,12337
[48] http://www.reuters.com/article/2008/01/16/us-biofuel-summit-hbio-petrobras-idUSN1660193320080116
[49] http://www.bp.com/sectiongenericarticle.do?categoryId=9033202&contentId=7060838#7219686

18. Production of other advanced biofuels

18.1 Summary

(i) Fischer Tropsch fuels

It is possible to make biofuels via the gasification of biomass into simple molecules of mainly hydrogen and carbon monoxide (called “syngas”), followed by a synthesis step known as the Fischer Tropsch (FT) process. The biofuels produced from these steps are hydrocarbons and are compatible with existing fossil fuels and transport fuel infrastructure. One such biofuel can be used to replace, or be blended with, petroleum diesel. It is commonly called synthetic diesel, syndiesel or FT diesel. Jet fuels can also be produced with this technology.

The production of liquid hydrocarbon fuels using gasification followed by synthesis already occurs at commercial scale using coal as feedstock. Challenges for adapting this technology to biomass feedstocks include:

- securing large quantities of biomass on a reliable, long term basis
- producing a clean syngas of appropriate composition
- operating at sufficient scale to allow biofuel production at competitive cost.

These biofuels are at the advanced research to early commercialisation stage of development but no commercial plants are being built or operated.

(ii) Pyrolysis biofuels

Fast pyrolysis is a process that converts woody material into a liquid called pyrolysis oil (or bio-oil). Charcoal and combustible gas are also produced during the pyrolysis process. The process will work with any form of biomass after the biomass is first reduced to a suitable particle size and moisture content.

Fast pyrolysis technology is already used commercially in a limited number of plants in Canada and the USA. While bioenergy applications may offer markets in the longer term, current markets for the pyrolysis oil are primarily for chemical production.

Pyrolysis oil is not a conventional hydrocarbon liquid. It can be used in boilers and furnaces to generate heat and power, but cannot yet be readily used in engines. Several groups have developed upgrading processes that use catalysts to convert pyrolysis oil into hydrocarbon transport fuels. Some have added a catalytic process to the initial pyrolysis step while others perform the upgrading in a process that follows the initial pyrolysis. It is expected that over the next few years the first large scale facilities making finished transport fuels will be built and trialled.

Some fast pyrolysis plants have been built at a commercial scale that requires less feed than proposed for commercial biomass to ethanol or syndiesel plants. This can assist in the commercial deployment of pyrolysis plants, as they can be built to utilise biomass feedstocks that are insufficient for the other technologies.

Preliminary costing work for a proposed commercial scale pyrolysis and upgrading plant indicates that it can provide competitively priced transport fuels[1].

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[1] http://www.dynamotive.com/comingsoon/resources/Dynamotive_Commercial_Case.pdf

(iii) Other advanced biofuel technologies

There are several other approaches to biofuel production that are also attracting significant interest and activity. These include:

- The use of supercritical water to break down woody material into a renewable crude oil suitable for subsequent processing to transport fuels in existing oil refineries
- Aqueous phase reforming, again to achieve a hydrocarbon liquid targeted for use as an intermediate feed to an oil refinery
- Fermentations to produce liquids other than ethanol
- Gasification followed by synthesis to produce methanol.

18.2 Fischer Tropsch biofuels

18.2.1 Overview of technology

This process for the manufacture of hydrocarbon fuels involves two main steps. The first step involves production of synthesis gas (or “syngas”) from a biomass feedstock. The second step involves the conversion of this gas into liquid fuel by processing the gas over a suitable catalyst. The synthesis process commonly used is called the Fischer Tropsch (FT) process. The overall process is often referred to as “Biomass to Liquids” or “BtL”.

Biomass gasification is a relatively well-developed technology, with large-scale biomass gasifiers having operated in several countries (including Australia). Gasification is a high temperature process, which operates in an oxygen-starved environment. The biomass generally needs to be pre-conditioned to obtain the appropriate biomass particle size, size distribution and moisture content to match the gasifier’s specification. The target syngas is rich in carbon monoxide and hydrogen. Similar gas can be made via gasification of coal and also from natural gas.

The original FT process was developed by German scientists almost 100 years ago[2]. It has already been used at large scale to make synthetic fuels, with the syngas feed produced by gasification of coal. Large scale, coal-based FT plants have been operated by SASOL in South Africa for some fifty years[3].

During FT synthesis the hydrogen and carbon monoxide molecules created by gasification are transformed into synthetic fuel according to the chemical equation:

$$\mathbf{CO + 2H_2 \dashrightarrow -CH_2- + H_2O}$$

Where $-CH_2-$ is a component of the synthetic fuel, ideally with a chain length of 18 carbon atoms to make synthetic diesel. Once the syngas is produced it is cleaned and conditioned, then passed over a catalyst tailored for the synthesis of the end product fuel. The gasification process can use a variety of biomass types as the objective is to transform the biomass into simple molecules of carbon monoxide and hydrogen.

Synthetic diesel made via the Fischer Tropsch process has exceptionally good fuel characteristics. It typically has a high cetane index of approximately 80 (cetane index is a measure of the ignition quality). This is substantially in excess of that of traditional diesel derived from crude oil. FT diesel also has a slightly higher calorific value compared to petroleum diesel, and low sulphur and aromatics contents. FT diesel may be used as a direct substitute for diesel, as this fuel can be produced to meet the specifications for petroleum diesel (although the density is slightly lower).

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[2] http://www.fischer-tropsch.org

[3] http://www.sasol.com/sasol_internet/frontend/navigation.jsp?navid=1&rootid=1

18.2.2 Industry status

Gasification of coal followed by FT synthesis has been carried out at commercial scale for some time, however gasification of biomass and FT synthesis is still pre-commercial. Companies that have investigated this process include the following:

(i) Choren

German company Choren built the world's first large scale BtL plant at Freiburg, Germany. This 'Beta' plant (the second large scale prototype and a scale up from the previous "alpha" plant) was designed with a gasifier of 45 MW thermal capacity and sized to convert some 65,000 tonnes dry biomass feedstock into 15,000 tonnes/year (18 ML/year) of syn-diesel. The plant was officially opened in April 2008 however it is not known whether it was successfully commissioned and operated. Choren launched insolvency proceedings in 2011. In February 2012 Linde Engineering purchased the Choren gasification business segment[4].

(ii) Xynergo

Xynergo is a Norwegian company that was established in 2008 by Norske Skog (one of the world's largest suppliers of newsprint and paper) and four forestry companies.

In May 2010 it was announced that Xynergo would collaborate with others to build a demonstration project to examine gasification/synthesis as technology to manufacture liquid fuels from wood[5]. However it was subsequently announced in November 2010 that Xynergo would cease operations due to an inability to secure new investment for the risk capital needed for final development and initial commercialisation of the technology[6].

(iii) Oxford Catalysts Group

The Oxford Catalysts Group (OCG)[7] and its subsidiary company Velocys have developed micro-channel process technology and specialised catalysts for FT synthesis. OCG states that this approach allows efficient FT synthesis at much smaller scale than traditional FT plants (as used in the South African coal industry for example).

OCG has operated a pilot plant in Austria from 2010[8]. This plant used synthesis gas produced by the existing biomass gasifier in the town of Güssing and was sized to produce approximately 150 litres per day of fuel.

In 2011 OCG supplied two larger micro-channel reactors for a biofuels demonstration plant to be built in Brazil and sized to produce approximately 2.6 million litres of synthetic diesel per year. The Brazilian plant is due to begin operations in 2012[9].

(iv) Rentech

Rentech[10] is a US company that has developed technology for the conversion of synthesis gas into liquid fuels, which may then be upgraded in a separate process (by technology provider UOP) to transport fuels and chemicals.

Rentech has built and operated a pilot plant in Colorado, USA that converts synthesis gas into approximately 1,500 litres of fuels per day. To date that plant has operated on fossil fuel feeds.

In 2010 Rentech signed a letter of intent with Solena for its technology to be used in Solena's project Green Sky in the United Kingdom[11]. The letter of intent indicated that construction would commence in 2012 and the plant would produce approximately 100 M litres of jet fuel and naphtha per year.

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[4] http://www.the-linde-group.com/en/news_and_media/press_releases/news_120209.html
[5] http://www.thebioenergysite.com/news/6181/first-steps-towards-green-diesel
[6] http://www.risiinfo.com/techchannels/powerenergy/Xynergo-decides-to-initiate-a-process-to-cease-biofuel-operations.html
[7] http://www.oxfordcatalysts.com/index.php
[8] http://www.oxfordcatalysts.com/press/pr/ocgtpr20100816.php
[9] http://www.oxfordcatalysts.com/press/pr/ocgtpr20110518.php
[10] http://www.rentechinc.com/index.php

During 2011 Rentech built a 20 ton per day gasifier at the Colorado site so that the fuels pilot plant could be operated on syngas derived from biomass. Mechanical completion of the gasifier was announced late in 2011 and activities with the unit are funded through to the end of 2012[12].

Also in late 2011 Rentech announced a strategy of reduced spending for project development and R&D with a focus on only moving ahead with projects that had co-investment from partners. It appears that work on its proposed commercial scale "Olympiad Project" in Ontario Canada is on hold until co-investors can be secured[13].

(v) Solena

Solena intends using plasma gasification then FT synthesis to make light oils and waxes, which may then be upgraded to fuels. Proposed products include transport fuels, naphtha and electricity from heat and tail gas. A presentation made in 2009[14] stated that Solena's plasma gasification technology has been under development for more than ten years. A pilot plant developed by the Solena Group has been operated in North Carolina for several years and plasma gasification has been used in a range of waste disposal applications around the world[15].

Solena has announced a number of commercial initiatives:

- A first commercial plant in the UK is expected to use half a million tonnes per year of municipal rubbish as feed for a plasma gasifier and FT processing that will ultimately produce 50,000 tonne per year of jet fuel (for use by British Airways) and 33 MW of electricity. It is expected to be in production 2015[16]. The FT technology for this plant will be provided by Oxford Catalysts[17].
- A commercial plant in California has also been announced[18]. This plant is expected to use 550,000 tpa of urban and agricultural wastes and be operational by 2015.
- Solena signed an agreement with Qantas in 2011 to "investigate the feasibility of a waste-based aviation fuel production plant in Australia"[19].

(vi) Thermochem Recovery International (TRI)

US company TRI also promotes the use of gasification then FT synthesis to make renewable fuels. TRI has operated a commercial scale gasifier in Canada for several years. It has also operated an integrated Process Demonstration Unit (gasification and FT) in North Carolina, which was built in 2009 [20]. This unit is sized to process four dry tons of biomass per day and during 2012 it achieved a 1,000 hour trial run as an integrated system.

A commercial biofuels project has been proposed at an existing paper mill in Flambeau River Park Falls in Wisconsin. A capital cost of US$300 M has been quoted for a plant sized to manufacture 70 ML/year (19 M US gal/year) of fuel and waxes plus power and steam. US Government funding support appears to be under negotiation[21].

18.2.3 Plant size and feed supplies

Choren stated that its full scale plants would use 1 million dry tonnes of wood per year as feed. This is approximately to 2 million tonnes of green wood.

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[11] http://www.rentechinc.com/pdfs/Solena%20RTK%20Final%2011%209%2010.pdf

[12] http://www.rentechinc.com/pdfs/RTK%202Q12%20Earnings%20Press%20Release%20FINAL%208%2010%2012.pdf#zoom=80

[13] http://phx.corporate-ir.net/phoenix.zhtml?c=66629&p=irol-newsArticle&ID=1639960&highlight=

[14] http://www.slideshare.net/smotycka/solena-technology-amp-bio-energy-platform-usaidampusea-01-sept09

[15] http://sgibiopower.com/files/plasma.pdf

[16] http://www.solenafuels.com/sites/default/files/The%20Guardian%20March%2016%202012.pdf

[17] http://www.solenafuels.com/sites/default/files/Oxford%20PR%2003%20July%202012.pdf

[18] http://www.solenafuels.com/node/47

[19] http://www.ethicalinvestor.com.au/index.php?option=com_content&task=view&id=4037&Itemid=402

[20] http://www.tri-inc.net/pdfs/Paper%20360%20PDU%20Article.pdf

[21] http://www.businessnorth.com/exclusives.asp?RID=3702

By comparison, the Tasmanian pulp mill proposed by Gunns is sized to use 3.2 million tonnes of green wood feed per year[22] and the expanded Visy pulp mill in Tumut NSW uses approximately 2 million green tonnes per year[23]. Feed supply to operate even one of the plants proposed by Choren in Australia would require one or more of:

- A major redirection of wood out of the pulp export markets
- Extensive new tree planting
- Utilisation of agricultural residues such as wheat stubble or sugar cane trash
- Utilisation of woody weeds such as the prickly acacia (*Acacia nilotica*) that grows extensively between Townsville and Mt Isa.

The price for export wood chips has been volatile over recent years and biofuels may represent a commercially-competitive alternative use for these chips in the longer term. The other potential feeds above are not accurately costed or quantified for any given site, so sourcing a low-risk feed supply for a new syn-diesel plant of this size appears to be a significant undertaking.

In contrast to the size of plant suggested by Choren, OCG is developing FT technology at a much smaller scale and describes it process as being commercially viable at 500 ton per day of wood feed. In May 2012, OCG started its first commercial scale FT module, which is sized to produce approximately 1.3 Ml of fuel per year[24]. A commercial plant is expected to comprise multiples of these modules.

18.3 Fast pyrolysis

18.3.1 Making pyrolysis oil

Pyrolysis is the term used to describe the heating of biomass in the absence of air or, more importantly, oxygen. With no oxygen present the biomass cannot burn. Pyrolysis is not an exothermic reaction and heat is not produced. Instead, external heating of the biomass is required. This heat distils (breaks down) the biomass into solid, liquid and gaseous fractions. The temperature, time for heating and other variables determine whether the pyrolysis process produces predominately charcoal solids (typically via slow pyrolysis) or liquids (typically via fast pyrolysis)[25].

Fluidised bed reactors are popular for fast pyrolysis as they provide rapid heat transfer and offer good control for the pyrolysis reaction. The reactor developed by Canadian company Dynamotive[26] is a fluidised bed; a large bed of sand that is “fluidised” by passing inert gas through the base of the reactor. Heat is applied to the sand via heating tubes and biomass is introduced to the hot sand where it rapidly reaches the target temperature and is pyrolysed. All the pyrolysis products leave the reactor as an overhead stream. From this stream the charcoal is separated (via cyclones), the liquid is captured in a large quench vessel (via contact with cooled bio-oil) and the gases that cannot be condensed are returned to be used as fuel in the combustor that keeps the actual pyrolysis reactor at the required temperature. There is no waste and no effluent streams from such a pyrolysis process. The commercial pyrolysis plants developed by Ensyn[27] also use fluidised bed reactors.

The fundamentals of pyrolysis are widely researched. In Australia, Melbourne University, Monash University and Curtin University have all operated research scale pyrolysis processes over recent years. World-wide, there are more than 80 small scale reactors[25]. IEA Bioenergy Task 34[28] links many research groups and provides general information about pyrolysis.

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[22] http://www.gunnspulpmill.com.au/faqs.html

[23] P 12 - http://www.planning.nsw.gov.au/asp/pdf/06_0159_visy_tumut_expansion_preliminary_assessment.pdf

[24] http://www.oxfordcatalysts.com/press/pr/ocgtpr20120523.php

[25] Review of fast pyrolysis of biomass and product upgrading, by AV Bridgwater. Biomass and Bioenergy Vol 38 -March 2012 pages 68-94

[26] www.dynamotive.com

[27] www.ensyn.com

[28] www.pyne.co.uk

18.3.2 Using pyrolysis oil

Pyrolysis oil can be used as a fuel in its own right or in combination with other fuels. It can be used in furnaces, kilns and boilers to produce heat, steam and electricity. It has also been used to demonstrate electricity generation via an industrial gas turbine coupled to a 2.5 MWe generator[29].

Tests carried out on pyrolysis oil as a boiler liquid fuel show that its combustion is feasible, notwithstanding:

The water present in pyrolysis oil can make it more difficult to ignite. The combination of high temperature required for ignition and the possibility of thermal degradation of the oil requires precise ignition chamber temperature control.

The water content of pyrolysis oil results in higher (water) vapour content in exhaust gases. The resulting higher dew point may limit the potential for energy recovery from exhaust gases in large boilers.

Pyrolysis oil is generally acidic, and may contain suspended solid matter. These attributes will need to be considered in the design of systems for storage, handling and combustion.

Table 18-1 below provides a comparison of several parameters of a pyrolysis oil with petroleum diesel. Pyrolysis oil typically has an energy density of 60% of that of diesel on a volume for volume basis and some 40% on a mass for mass basis.

Table 18-1 Pyrolysis oil properties compared with diesel fuel

Parameter	Units	Pyrolysis oil (wood based)	Diesel
Higher Heating Value	MJ/kg	16-19	42
Flash Point	oC	48-55	35-60
Viscosity	cSt	8 (60 oC)	6
Moisture	wt%	20-25	0
Density (25oC)	kg/litre	1.2	0.84
Surface Tension	mN/m	35-39	29
Acidity	pH	2-3	5
Solids (char)	wt %	0.01-0.2	-
Ash	wt %	<0.02	0.01

18.3.3 Upgrading pyrolysis oil

Pyrolysis oil is not readily used in engines, either as a discrete fuel or in blends with diesel or petrol. For this reason several groups are examining processes to upgrade pyrolysis oil into renewable hydrocarbons that will be fully compatible with existing hydrocarbon processing, distribution and application infrastructure. As an example, Dynamotive has developed a two stage process[30]:

- Stage one is called hydro-reforming or hydro-deoxygenation. Hydrogen is added to the pyrolysis oil in a reactor that incorporates an industrial catalyst. Water and acetic acid are removed from the pyrolysis oil and the energy content of the remaining oil is substantially increased. The resulting liquid is a hydrocarbon and is completely miscible with other hydrocarbon fuels, with an energy content that is almost 90% of diesel.
- A second processing stage further upgrades this fuel. Additional hydrogen is added to the fuel and additional oxygen is removed. The general outcome is to produce liquid hydrocarbons with

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29 http://www.dynamotive.com/assets/resources/corporate_brochure.pdf
30 http://www.dynamotive.com/assets/resources/2011/upgrading/BioOil-Upgrading-Report.pdf

energy content and boiling point curves very similar to transport fuels such as petrol, diesel and jet fuel. This stage can occur in a purpose-built reactor or in an existing oil refinery.

Yields of upgraded hydrocarbon liquids from the Dynamotive process are quoted to be in the vicinity of 300 litres per tonne of dry biomass feed.

18.3.4 Feed supplies

One of the useful attributes of pyrolysis is its ability to process almost any form of woody biomass. For successful fast pyrolysis using fluidised beds the biomass feed requires preparation:

The biomass must be ground into small particles. This allows the particles to heat rapidly when they are introduced into the pyrolysis reactor and facilitates the conversion to liquid product.

The biomass will preferably contain around 10% moisture or less. Moisture in the biomass feed carries through the pyrolysis process and dilutes the oil that is produced.

The sizes of fast pyrolysis plants, and thus their biomass requirements, are currently dictated by the commercial work carried out by each technology provider:

- Dynamotive's first commercial plant was designed for 100 tonne per day of dry wood feed (at approx. 8% moisture content). More recently Dynamotive has built a plant that process 200 tonnes per day of dry wood feed (this equates to approximately 130,000 green tonnes of wood feed per year).
- Ensyn has built several biomass pyrolysis plants at sizes up to 100 tonnes per day of feed (66,000 green tonnes per year). Feed supply is usually saw mill wastes.

Fast pyrolysis can provide commercial plant designs at a scale that allows processing plants to be built for far less biomass feed than is expected to be required for ethanol or syn-diesel. Because of the speculative nature of cost estimates for these technologies it is not clear how the relative sizes of commercial plants will impact on the relative costs of the fuels produced. However potential benefits of a smaller commercial plant (pyrolysis versus ethanol or syn-diesel) come from:

- The ability to utilise existing feed supplies that would be insufficient for larger biofuel plants.
- Less upfront cost and risk associated with establishing and maintaining feed in situations where new feed supplies are required.
- Lower capital costs for processing plants.

18.3.5 Industry status

(i) Dynamotive & IFPEN

The fast pyrolysis process commercialised by Canadian company Dynamotive heats biomass feed to almost 500^{O}C in approximately one second, and typically converts approximately two thirds of the biomass feed into liquid pyrolysis oil. The remaining biomass is converted into charcoal and non-condensable gases. Dynamotive has demonstrated this technology at commercial scale in two separate plants in Ontario, Canada.

Dynamotive has also developed an upgrading process, which has been demonstrated at laboratory scale. The upgrading process involves hydro-reforming then hydro-treating to reduce oxygen content and increase hydrogen content. Dynamotive has announced collaboration with IFP Energies nouvelles and Axens for the further development of this technology[31].

Dynamotive is represented in Australia by Renewable Oil Corporation Pty Ltd.

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[31] http://www.dynamotive.com/2011/11/30/dynamotive-ifp-energies-nouvelles-axens-complete-binding-heads-of-agreement-for-commercial-development-of-pyrolysis-oil-upgrading/

(ii) Envergent Technologies (Ensyn UOP)

Envergent Technologies is a US company that uses the fast pyrolysis technology of Canadian company Ensyn. Ensyn's fast pyrolysis technology (called Rapid Thermal Processing – "RTP") has been demonstrated at large scale in the USA for many years, largely through the manufacture of pyrolysis oil for the subsequent manufacture of food flavourings. The US plants typically process approximately 45 tonne per day of dry wood feed. Ensyn's largest and most recently built plant (at Renfrew in Ontario, Canada) is designed to process 100 tonnes per day of dry feed.

Pyrolysis oil made by the Ensyn process has been upgraded in the laboratory, using hydro-processing technology from UOP, a US company that specialises in technologies for the oil and gas industries[32]. In August 2011 Envergent (a joint venture between Ensyn and UOP) announced that it had commenced site work for a demonstration unit in Hawaii to convert cellulosic biomass into green transportation fuels. The demonstration plant is expected to be operational in 2014[33].

(iii) KiOR

KiOR is developing a pyrolytic process that differs from Ensyn and Dynamotive in that a catalyst is used during the initial reaction. KiOR refers to this process as fluid catalytic cracking because of its similarity to the initial crude oil cracking reactors found in conventional oil refineries.

The initial reaction creates solid, liquid and gaseous products[34]:

- The charcoal or "coke" is burnt off the catalyst in a separate reactor, which also provides heat for the main reaction.
- The renewable crude oil is further refined in a hydro-treater to make petrol and diesel blending stock.
- The combustible gases are used to generate steam and electricity for use within the plant.

KiOR has built a demonstration plant in Texas, sized to produce up to 2,400 litres per day of crude oil[35]. KiOR has also upgraded some of this crude to finished transport fuels.

A commercial scale prototype plant has recently been built in Columbus Mississippi, and is scheduled for commercial start-up in the second half of 2012[36]. This plant is sized to use 500 bone dry ton per day biomass (approx. 300,000 green tonne/year) for production of 40 Ml/year of mixed fuels[37].

KiOR notes that its preferred scale for subsequent commercial plants is 1,500 dry ton per day of feed (approx. 1 million green tonne per year). The first such plant is targeted for Newton, Mississippi.

(iv) CRI Catalyst Company

CRI Catalyst Company (CRI) is part of CRI/Criterion Inc., the global catalyst company of the Shell group[38]. CRI has licensed a biofuel process from the Gas Technology Institute (GTI), which is known as "Integrated Hydropyrolysis and Hydroconversion" (IH2). IH2 is described as an advanced pyrolysis technology that uses low pressure hydrogen together with a proprietary catalyst to convert biomass into transport fuels[39]. GTI opened a 50 kg/day pilot plant to demonstrate the technology in 2012[40]. The company plans to begin basic engineering on a commercial plant design in 2014[41], which suggests that a first commercial plant could be operational as early as 2016.

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[32] http://www.envergenttech.com/technology.php
[33] http://www.uop.com/honeywells-uop-breaks-ground-facility-convert-biomass-green-transportation-fuels/
[34] http://www.kior.com/content/?s=11&t=Technology
[35] http://www.kior.com/content/?s=6&s2=32&p=54&t=Demonstration-Facility
[36] http://www.kior.com/content/article.php?Atricle=23&s=2&s2=35&p=35&t=News-and-Events
[37] http://www.kior.com/content/?s=6&s2=56&p=56&t=Production-Facilities
[38] http://www.cricatalyst.com/home/content/cri_catalyst/about/
[39] http://www.greencarcongress.com/2011/08/aquaflow-20110823.html
[40]http://www.cricatalyst.com/home/content/cri_catalyst/in-the-news/media_releases/fueling_the_future.html
[41] Hydrocarbon Fuels from Biomass using IH2 Technology: 9th Europe Workshop Biotechnology of Microalgae http://www.cricatalyst.com/home/content/cri_catalyst/catalysts/renewables/presentations

New Zealand company Aquaflow has a sub-licensing agreement with CRI for the IH2 technology, and plans to utilise it on projects that involve both algae and biomass[42].

18.4 Other technologies

The preceding sections describe a number of general technologies currently in use or close to commercialisation. There are several other approaches to biofuel production that are also attracting interest. These include:

- The use of supercritical water to break down woody material into a renewable crude oil suitable for subsequent processing to transport fuels in existing oil refineries.
- Aqueous phase reforming, again to achieve a hydrocarbon liquid suitable to be used as an intermediate feed to an oil refinery.
- Fermentations to produce liquids other than ethanol.
- Gasification followed by methanol synthesis.

18.4.1 Supercritical fluids

A supercritical fluid is a fluid that has been taken to temperatures and pressures above its vapour-liquid critical point. Above this point the clear distinction between vapour and liquid ceases to exist and the supercritical fluid is considered to be able to diffuse through solids like a gas, while dissolving materials like a liquid[43]. This creates opportunities for the use of various substances in their supercritical state as alternatives to other solvents.

- Carbon dioxide is used as a supercritical fluid, for example in the removal of caffeine from coffee.
- Researchers have used methanol in its supercritical state for the transesterification of fats and oils to make biodiesel[44].
- Water may be used as a supercritical fluid above its critical point of 370^{O}C and 22 MPa (218 atmospheres). Its use to make biofuels is being assessed by groups in Australia and overseas[45,46,47]. In some cases the work examines the liquefaction of biomass to make sugars available for subsequent fermentation and in other cases the target products are hydrocarbon liquids.

Pilot and demonstration scale work with supercritical water has been carried out recently by companies in Australia and New Zealand.

(i) Licella

Australian company Licella is commercialising technology using supercritical water to make a bio crude from biomass. They call the process catalytic hydrothermal upgrading (CAT-HTR), and Licella's parent company Ignite Energy is seeking to apply the same technology to brown coal[48].

Licella's process produces a stable bio crude, which the company states can potentially be used as a marine fuel or upgraded via oil refineries to produce other hydrocarbons. Yields are quoted as 3.5

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[42] http://www.aquaflowgroup.com/projects/multi-green-fuel-demonstration-facility
[43] http://en.wikipedia.org/wiki/Supercritical_fluid
[44] Kunchana Bunyakiat, Sukunya Makmee, Ruengwit Sawangkeaw, and Somkiat Ngamprasertsith (2006). "Continuous Production of Biodiesel via Transesterification from Vegetable Oils in Supercritical Methanol". Energy and Fuels 20: 812–817.
[45] http://www.nt.ntnu.no/users/skoge/prost/proceedings/aiche-2005/topical/pdffiles/T7/papers/279f.pdf
[46] http://etd.auburn.edu/etd/handle/10415/1078
[47] http://agile-prod.ucc.usyd.edu.au/research/opportunities/opportunities/373?faculty=id8
[48] http://www.igniteer.com/projects/truenergy-partnership.html

barrels of bio crude per dry tonne of biomass[49]. Licella intends that these crude oils will be subsequently upgraded in conventional oil refineries to produce transport fuels[50].

Licella has recently opened a biocrude demonstration plant in NSW[51]. The plant is sized to process 3,300 dry tonnes of biomass per year through to renewable crude oil and Licella suggests that the design may be modularised, with three such units constituting a commercial plant capable of processing 10,000 dry tonnes of feed per year[52]. Commercially competitive operation at this scale could be a significant benefit when compared with proposed ethanol and syn-diesel plants requiring feed at several hundred thousand dry tonnes per year or more.

(ii) Solray Energy

Solray Energy[53] is based in New Zealand and uses a supercritical water reactor to process whole algal biomass into bio crude[54]. The company has built a pilot facility in Christchurch, New Zealand.

18.4.2 Aqueous phase reforming

Aqueous Phase Reforming (APR) involves the reforming of sugars into hydrogen, alkane-type hydrocarbons and chemical intermediates. This may be considered as an intermediate feed that may be further processed into a range of transport fuels in stand-alone facilities or conventional oil refineries. APR occurs in the aqueous phase over catalysts, at temperatures of 180 – 300 ^{0}C and pressures of 10 – 90 Bar.

APR technology has been investigated by several research groups including the University of Wisconsin[55] and the US Government's Pacific Northwest National Laboratory[56]. It is also the subject of considerable work by US company Virent Energy Systems, which has formed associations with a number of organisations including Cargill, Shell and Honda. In November 2009 Virent commenced operations of its "Eagle" pilot plant, capable of producing approximately 40,000 litres per year (5 litres per hour) of fuels[57]. In March 2012 Virent announced that it had successfully made petrol and jet fuel from cellulosic sugars using its proprietary "Bioforming" process[58]. The company is also developing technology for the production of renewable plastics such as paraxylene.

18.4.3 Novel fermentations

(i) Amyris

Amyris is a US company that uses fermentation to convert sugars into a range of fuels and chemicals[59]. It produces farnesenes[60] which may be further processed to make chemicals including isoprenoids as fuels. Isoprenoids are molecules made up of two or more units of isoprene (2-methyl 1,3 butadiene).

In 2011 Amyris commissioned small scale industrial facilities to make these chemicals in the US[61], Spain[62], and Brazil[63], using modified yeast for the fermentation of sugars from adjacent sugar

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[49] "Licella's hydrothermal reactor(biomass to stable biocrude) – commercialisation game plan". Paper presented by Mr Perry Toms, Licella, at the Annual Conference of Bioenergy Australia, December 2009.

[50] http://www.licella.com.au/end-products/transport-fuels.html

[51] http://www.licella.com.au/news/175-cdp-minister-martin-ferguson.html

[52] http://activepaper.smedia.com.au/Repository/getFiles.asp?Style=OliveXLib:LowLevelEntityToPrint_OGB&Type=text/html&Locale=english-skin-custom&Path=OGB/2009/11/01&From=Archive&ID=Ar02203

[53] http://solventrescue.co.nz/

[54] http://www.sift.net.nz/blog/solray-energy-opens-new-algae-to-bio-crude-oil-plant/

[55] http://www.cheric.org/ippage/g/ipdata/2003/01/file/g200301-3601.pdf

[56] http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/review04/hpd_p6_king.pdf

[57] http://www.virent.com/wordpress/wp-content/uploads/2011/10/Fuel-For-Thought-Summer-2011-FINAL.pdf

[58] http://www.virent.com/news/virent-makes-jet-fuel-from-virdias-cellulosic-biomass/

[59] http://www.amyris.com/

[60] http://en.wikipedia.org/wiki/Farnesene

[61] http://www.amyris.com/en/newsroom/210-amyris-commissions-commercial-production-facility-at-tate-a-lyle-

[62] http://www.reuters.com/article/2011/07/25/idUS111244+25-Jul-2011+BW20110725

[63] http://www.businesswire.com/news/home/20110429005211/en/Amyriss-Commercial-Production-Facility-Complete-Operational

suppliers. In 2012 Amyris announced collaboration with oil company Total for up to US$82 M to be spent over three years.

(ii) Gevo

Gevo is a US company that has focused on microorganisms that ferment sugars through to iso-butanol instead of ethanol. Iso-butanol is a four carbon alcohol and Gevo believes that it offers advantages as a fuel when compared with ethanol because of its chemical properties, acceptability for higher blends with petrol, and adaptability for upgrading to petrol and jet fuel[64]. Gevo has operated a pilot plant and is now seeking to achieve commercial scale production by modifying existing ethanol facilities in the USA so that they can produce and recover iso-butanol instead of ethanol. Gevo's first such retrofitted facility, at Luverne Minnesota, started operation in May 2012 and is expected to reach full capacity by the end of 2013[65].

(iii) Solazyme

Solazyme uses algae to make fuels and chemicals, but not in the same way as the photosynthetic algae described in Chapter 20. Solazyme uses heterotrophic algae, which grow via fermentation of sugars rather than photosynthesis of sunlight. Solazyme seeks to produce fuels and also chemicals and nutritional products:

- It is building a food ingredient plant at an existing industrial facility in Lestrem in France with Roquette as partner. This 300 tonne/year facility is expected to start production in 2012 and eventually be expanded to 5,000 tonne/year[66].
- It is adapting an existing fermentation plant in Peoria, Illinois to make approx 2 ML/y of algal oil[67]. This plant is expected to come on line in 2012[68].
- It has an order to provide R&D quantities of transport fuels made from algae and used cooking oil to US Navy at average price of approximately US$7/litre[69]. It has also announced collaboration with Qantas to explore potential for fuel production in Australia[70].
- Solazyme is planning a commercial scale plant in Brazil with Bunge to make 100,000 tonne/year of triglyceride oils at a new facility alongside an existing sugar mill. Start up of the new facility is planned for 2013[71].

(iv) Zeachem

Zeachem's core technology utilises microorganisms that convert sugars to acetic acid and other chemicals rather than directly to ethanol. The acetic acid can be converted to ethyl acetate. Around this core technology Zeachem proposes to:

- Use cellulosic feeds that will be separated into sugars and lignin
- Use the lignin in a separate gasification process to produce syngas, from which hydrogen will be extracted.
- Use the hydrogen to hydrogenate the ethyl acetate through to ethanol, which may then be used as a biofuel.

The acetogenic microorganisms used by Zeachem are not yeasts and the metabolic pathway that they utilise to make acetic acid offers the potential for increased final yields of ethanol compared with yeast fermentations.

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[64] http://www.gevo.com/our-business/our-markets/

[65] http://www.hydrocarbonprocessing.com/Article/3036474/Latest-News/Gevo-starts-up-commercial-bio-based-isobutanol-plant-in-Minnesota.html

[66] http://solazyme.com/media/2011-10-24

[67] http://www.greenworldinvestor.com/2011/03/16/algae-biofuel-green-company-solazyme-100mm-ipo-financialspartnerscostspros-and-cons-tempting-though-risky

[68] http://solazyme.com/media/2011-11-07-0

[69] http://www.bloomberg.com/news/2011-12-05/navy-to-buy-12-million-of-advanced-biofuels-in-record-purchase.html

[70] http://solazyme.com/media/2011-02-10

[71] http://solazyme.com/media/2012-04-03

In January 2012 Zeachem announced it had completed the construction of a demonstration plant for the core technology in Boardman, Oregon[72]. During 2012 it expects to build other components that will in combination allow the production of up to 1 ML of ethanol/year in an integrated demonstration plant.

Also in January 2012 the company was selected for a USDA loan guarantee of US$ 232.5 M, which will assist with funding for a proposed 100 Ml/ year full scale facility near the demonstration plant[73].

18.4.4 Gasification and methanol synthesis

US company Sundrop Fuels has developed a proprietary gasifier called the “Radiant Particle Reactor” which gasifies biomass with the aid of external energy (natural gas, electricity or concentrated solar power) and mixes the finely ground biomass with natural gas before the gasification step[74]. The relative inputs of natural gas and biomass are not specified. A pilot plant was built in 2009 and preliminary engineering design for a full-scale facility was announced in May 2012[75]. A first full-scale facility is expected to be built in Louisiana, USA and be capable of producing up to 200 ML of transport fuels per year. The plant is expected use syngas-to-methanol and then methanol-to-gasoline (MTG) technologies that have previously been applied to other feed materials.

This first commercial plant is expected to cost approximately $450 to $500 million. Subsequent commercials plants are expected to be four times larger than the first plant.

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[72] http://www.zeachem.com/press/pressrelease010512.php
[73] http://www.zeachem.com/press/pressrelease012612.php
[74] http://www.sundropfuels.com/Benefits/rp-reactor
[75] http://www.sundropfuels.com/assets/white_papers/18.pdf

19. Costs for biofuels

19.1 First generation ethanol

With variability in feed price, plant size and cost, and government incentives for renewable fuels, it can be difficult to point to a definitive cost for first generation ethanol. Producers in Australia and elsewhere are operating profitably in spite of different feeds, plants and subsidies. Other project developers in Australia and overseas have cancelled projects because commercial returns were expected to be inadequate.

A number of major companies around the world offer design or turnkey packages for ethanol facilities and the costs and designs for first generation ethanol plants are well understood by plant suppliers and operators. Reports are available that describe the nature and costs of US grain to ethanol plants in some detail[1]. The 2010 report “Biofuel Costs, Technologies and Economics in APEC Economies” [2] provides detailed analysis of the capital and operating costs, financial returns and co-product benefits for US and Brazilian ethanol plants and also selected biodiesel plants.

A 2006 study by the Western Australian Department of Agriculture[3] examined the costs for several proposed grain to ethanol plants. Plants were based on the dry mill approach, to manufacture ethanol and also cattle feed[4]. A 40 Ml/year plant at Dalby in Queensland was expected to cost $54 M and 90Ml/year plants in NSW and Victoria were expected to cost $82M each. A plant has subsequently been built at Dalby however the other plants have not been built.

19.2 Biodiesel

(i) Feedstock

Feedstock is generally a major cost component for biodiesel manufacture. Feedstocks for manufacture of biodiesel include used cooking oil (UCO), animal fats (tallow), and vegetable oils such as palm oil and canola oil. Virtually all biodiesel produced in Australia at present is made from UCO or tallow[5], which are available at prices that allow biodiesel manufacture to be commercially viable. Larger scale production of biodiesel in Australia appears to be limited by lack of suitable feedstock at an acceptable or consistent price. Over recent years the price of palm oil (a common biodiesel feedstock overseas) has fluctuated from less than US$500 per tonne to more than US$1,000 per tonne[6]. In 2011 the price for crude palm oil in Malaysia was approximately A$1,000 per tonne[7] or A$1 per litre of biodiesel. The FOB price for canola oil in Canada has been above A$1,000 per tonne since 2010[8]. At the same time the wholesale price of diesel in Australia (before excise and GST) averaged $0.88 per litre[9].

Tallow is sometimes presented as a low value or waste product from the livestock industry but in reality it is a well traded commodity that is also a price follower of palm oil[10]. Whereas the ATSE Biofuels report in 2008 quoted tallow at $450 per tonne[41], it was quoted in December 2009 at $685 per tonne ex-works[10]. Australian prices reached a record high of more than $1,000 per tonne in 2011[11].

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[1] http://dc.aces.uiuc.edu/policy/research_reports/ethanol_report/
[2] http://www.biofuels.apec.org/pdfs/ewg_2010_biofuel-production-cost.pdf
[3] http://www.agric.wa.gov.au/objtwr/imported_assets/content/sust/biofuel/200601_bfgrainethecon.pdf
[4] http://beef.unl.edu/c/document_library/get_file?uuid=4ea342c5-839f-45c6-b166-667509fd8296&groupId=4178167&.pdf
[5] http://www.biofuelsassociation.com.au/index.php?option=com_content&view=article&id=59&Itemid=67
[6] http://www.mongabay.com/images/commodities/charts/palm_oil.html
[7] http://palmoil.com/exchanges/bmd/historical/2011_7/bmd_cpo_today_s_prices_2011_07_27_10_31_51
[8] http://www.canolacouncil.org/canolaprices.aspx
[9] http://www.aip.com.au/pricing/pdf/AIP_TGP_Data.xls
[10] http://www.meattradenewsdaily.co.uk/news/151209/australia____tallow_prices.aspx
[11] http://www.mla.com.au/files/2756a4a5-e2c8-4b22-99d3-a05100e091ab/co-products-summary-april-2012.pdf

(ii) Economics of production

Data presented by the Austrian Biofuels Institute[12] show the sensitivity of plant profitability to variants in a range of input and output costs. A 10% variation in feedstock price, product recovery or biodiesel selling price affected profitability by between 20 and 35 %. In contrast, 10% variation in plant capital or operating cost had an effect of less than 5% on profitability. More recent analysis for the APEC Energy Working Group also shows the impact of feedstock on product pricing[2].

19.3 Fuels from biomass

While no commercial-scale biomass to biofuel plants have been operated successfully yet, several full-scale plants were under construction at the same time this report was prepared, and cost and yield data have been published for some of these plants. Data are also available for cost estimates and financial modelling of biomass to ethanol plants, developed over many years by the US National Renewable Energy Laboratory (NREL).

(i) Ethanol via hydrolysis and fermentation

In May 2011, NREL published a report on the process design and economics for biochemical conversion of biomass to ethanol[13]. This report builds on design and costing work undertaken by NREL over more than ten years. The conceptual design presented considers ethanol production economics as determined by 2012 conversion targets and "*n*th-plant"[14] project costs and financing. The biofuels plant that is modeled would process 2,000 dry tonne/day of biomass feed. Product yield is expected to be 76% of theoretical (270 litre ethanol per dry tonne) and annual production of ethanol is estimated to be 230 Ml. The total capital investment for this plant is estimated to be US$ 422.5 M.

NREL prepared a financial model for such a plant built in the USA, with assumptions for feedstock price, debt funding for the plant and after tax returns to investors. It was estimated that the financial target for the plant could be met if ethanol was sold at 86 US cents per litre of petrol equivalent.

(ii) Ethanol via gasification and fermentation

Ineos Bio uses gasification then fermentation to produce ethanol. A commercial scale plant is under construction in Florida and is due to commence operation in the second half of 2012.

Published data from Ineos Bio indicates this first commercial scale plant will have a capital cost of US$130 M[15] and use 300 dry tons per day of biomass[16] (90,000 dry tonnes per year) to make up to 30 ML/year (8 million US gall/year) of ethanol. The plant will also generate approximately 6 MW of electricity, mainly for use within the plant.

(iii) Hydrocarbon fuels via catalytic pyrolysis and upgrading

KiOR uses catalytic pyrolysis then upgrading to manufacture hydrocarbon liquids. A demonstration plant has already been built and KiOR is building a commercial plant in Mississippi that is scheduled for start up in the second half of 2012.

Data published by KiOR for this prototype commercial plant indicates a capital cost of US$222 M and biofuels output of 42 ML/year (11 million US gall/year) of hydrocarbon fuels[17]. This plant is sized to process 500 dry tons per day which, at 330 day per year of operation, is equivalent to 150,000 dry tonne per year. These figures suggest a biofuel yield of 280 litre per bone dry tonne of feed.

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[12] Best case studies on biodiesel production plants in Europe. Prepared by the Austrian Biofuels Institute for IEA Bioenergy Task 39, subtask biodiesel, Feb. 2004

[13] NREL/TP-5100-47764

[14] The "nth plant" is a plant that is built when process technology and plant operation are well understood. Such a plant is expected to provide capital and operating cost efficiencies over prototype commercial plants.

[15] http://www.ineosbio.com/94-Indian_River_BioEnergy_Center.htm

[16] http://www.ineosbio.com/77-News_coverage-22.htm

[17] http://www.kior.com/content/?s=6&s2=56&p=56&t=Production-Facilities

(iv) Commercial prototypes versus mature technology

It is expected that early examples of commercial biofuel plants will cost more than later examples, as the latter will have the advantage of design and operational experience and economies of scale. For the renewable energy industry and also many manufacturing industries, it is routine for unit costs of production to reduce over time[18].

The US National Renewable Energy Laboratory (NREL) has examined the likely costs of large commercial ethanol plants as commercial prototypes and nth plants, the latter reflecting cost savings to be expected with technology and industry maturity[19]. The commercial prototype is referred to as the “pioneer plant” and NREL’s analysis suggests that ethanol from this first plant could cost from 47% to 108% more than ethanol from the nth plant, with the most likely outcome being a cost increase of 69%. Looked at from the perspective of the first plant, if given the opportunity to reach maturity, the industry could be expected to produce ethanol at 1/1.69 or 60% of the cost of the ethanol from the commercial prototype.

CRI Catalysts have published data for production of hydrocarbon biofuels in a hypothetical nth commercial plant, reflecting the economies that could be achieved through construction and operation of a number of plants[20]. This large plant is sized to process 2,000 tonne per day of wood at 50% moisture content (approx. 750,000 green tonne per year of wood feed). With a plant capital cost of US$ 256 M and a wood feed price of $40 per green tonne, a minimum selling price of US $ 0.46 per litre is estimated although it is not clear whether or not this selling price includes profit and a return to investors.

(v) Feed cost

The attractions of cellulosic feedstocks for manufacture of biofuels include the ability to avoid competition for the same feed from fuel production and food production, and potentially reduce variability in pricing as well as the competition for land. Some potential second generation cellulosic feeds are considered little more than a waste material (for example the waste straw and leaf from corn, wheat and sugar production) although they still have very real costs for collection and transport. The same applies to plantation residues in the softwood and hardwood industries – clearing them out of plantations can make replanting easier, but the cost of collection and transport must still be covered.

In the future, commercial advanced generation biofuel plants may secure their feed from existing or new forest industries, suggesting competition with the pulp chip market (which is also capable of significant price variation) or the need for new, dedicated crops. There is renewed interest in planting mallee eucalypts across dryland agricultural regions in Australia, initially for carbon sequestration and salinity mitigation and potentially for use as feed in ethanol plants. Other chapters of this report examine the delivered costs in Australia for these short rotation tree crops and also feedstocks such as straw and native grasses.

19.4 Cost comparison – biofuel versus electricity

A simple comparison is presented in Table 19-1 below to show the relative costs and returns for biofuels and electricity.

The example selected is based on a biomass feed supply equivalent to 150,000 tonnes per year measured on a dry basis. If woody residues are to be used as feed and typical moisture content is 50%, then approximately 300,000 tonnes of green feed would be required each year.

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[18] Process Industry Economics by Dr David Brennan, 1998. Published by Institution of Chemical Engineers, UK. ISBN 0 85295 391 7

[19] Techno-Economic Analysis of Biochemical Scenarios for Production of Cellulosic Ethanol by Hsu et al. NREL/TP-6A2-46588 June 2010

[20] http://www.cricatalyst.com/home/content/cri_catalyst/catalysts/renewables/presentations/#subtitle_1

Table 19-1 Example of simple payback calculation for electricity and biofuels

Parameter	Biofuel plant: Prototype (KiOR)	Electricity plant
Wood feed (green tonne/year)	300,000	300,000
Annual output	42 ML of biofuel	21.4 MW
Annual energy output (GJ/year)	1,470,000	616,000
Assumed product selling price	$1.26 per litre	$100/ MWh
Annual product revenues ($M/year)	53	17
Estimated capital cost ($M)	222	67
Simple payback in years (capital cost divided by gross revenues)	4.2	3.9

The electricity plant is based on a conventional boiler and steam turbine and assumes a plant using mature steam cycle technology. For the biofuel plant the data for KiOR's commercial prototype is used. It was noted above that maturity in the biofuels sector could drive costs down by 40%, suggesting that over time the biofuels sector could be the more financially attractive bioenergy application.

The product selling prices have been developed as follows:

- The price for biofuels is $1.26 per litre. 88 cents per litre is the average wholesale price paid for diesel across Australia over the 6 months to 1 February 2012 as calculated from data provided by the Australian Institute of Petroleum[21]. (The consumer pays a higher price, which includes a retail margin, excise and GST.) To this, 38.143 cents per litre has been added, which is a rebate based on current government legislation to support renewable fuels[22].

- The price for electricity is assumed to be $100/MWh. This is made up of $60/MWh as the cost for the electricity and $40/MWh for the Large Scale Generation Certificates (LGC's) under the Australian Government's Renewable Energy Target[23]. Actual values for electricity vary with location and time, and the price for LGC's is influenced by supply and demand and the penalties for non-compliance.

The capital cost of the biofuel plant is as reported by KiOR. This is for a prototype commercial plant. The US price has been translated directly to Australian dollars. The cost of the electricity plant has been determined from the data provided in Chapter 15.

Operating costs:

- for the electricity plant have been described in Chapter 15. They include energy used in the plant for electric drives, labour, maintenance and consumables such as water and water treatment chemicals for cooling towers.
- for the biofuels plant have not been published. They too will include energy, labour and maintenance costs. They will also include the cost of hydrogen that is used to upgrade the liquids made in the initial reactor. Energy costs may include feed drying, as many biofuel processes require feed with low moisture content, in contrast to electricity plants that can accept feed with moisture content of 50% or greater.

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[21] http://www.aip.com.au/pricing/tgp/index.htm
[22] http://law.ato.gov.au/atolaw/view.htm?docid=PAC/20040041/4
[23] http://ret.cleanenergyregulator.gov.au/About-the-Schemes/lret

20. Microalgae

20.1 Introduction

Microalgae are microscopic, plant-like, largely photosynthetic organisms belonging to a number of Phyla (major taxonomic groups). They are extremely diverse and can be found in most habitats of the world including fresh and sea water, salt lakes, soil, snow and on surfaces such as rocks and the bark of trees with an estimated 30-40,000 species. The size of unicellular microalgae ranges from about 1 µm to more than 100 µm. Many species also form colonies and chains. Some are motile, while others have no independent means of locomotion. The cell coverings of microalgae are also highly variable e.g., the wall-less cells of *Dunaliella*, cells covered with organic, calcareous or silicious scales such as in *Synura* or *Pleurochrysis*, the well developed organic walls of variable chemistry as in *Chlorella* and *Nannochloropsis*, and the complex ornamented silicon walls (valves) of the diatoms.

Figure 20-1 ***Dunaliella salina***

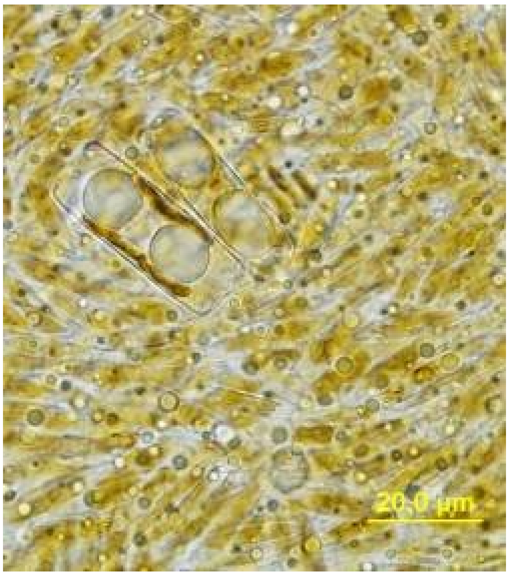

Figure 20-2 Mixed diatoms - Note the large oil droplets in the cells

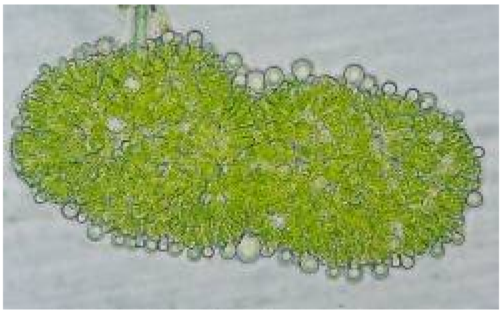

Figure 20-3 Botryococcus sp. Note the droplets of oil (hydrocarbons) being squeezed from the colony matrix

Many species of microalgae accumulate high amounts of lipids (fats), including triglycerides similar to plant oils as obtained from canola or soy beans, and which are suitable for conversion to biodiesel. Lipid contents of over 50% of dry weight have been reported for some species under certain conditions, especially when the algae are nitrogen-limited. A few species such as *Botryococcus braunii* also have a high content of long-chain lipids known as hydrocarbons which are similar to these found in oil deposits. It is thought that many of the fossil oil deposits were actually formed by this alga or a relative[1]. Algae also contain sugars and carbohydrates which can be fermented to produce ethanol.

Although commercial production of microalgae for biofuels does not yet occur, commercial production of microalgae for high value products such as pharmaceuticals, nutraceuticals and health food has been carried out for over 60 years. Commercial microalgae culture began with *Chlorella* production as a health food in the1950s in Japan and Taiwan, followed by *Spirulina* (*Arthrospira*) in the 1970s in Mexico and the USA, *Dunaliella salina* for the production of β-carotene in the 1970s in Australia, Israel and the USA, *Haematococcus pluvialis* for astaxanthin production in the 1980s in the USA, and *Crypthecodinium cohnii* for docosahexaenoic acid production in the USA. Commercial production of these algae is now taking place in many countries including Australia, China, India, Israel, Taiwan and the USA. Australia has the two largest commercial algae plants in the world, in Hutt lagoon, Western Australia (Figure 20-4) and Whyalla, South Australia. The plant at Hutt lagoon is the largest commercial algae production plant in the world, with a total pond area of about 720 ha.

Microalgae are of great interest as potential sources of renewable biofuels for the following reasons:

- They have high biomass productivities per unit area of land utilised compared with land plants. Some species divide more than one time per day under optimal conditions and some species have a high lipid content of 30 – 50% of their dry weight. This means that microalgae can have a high lipid productivity {*Lipid Productivity (g lipid* m^{-2} day^{-1}*) = growth rate x lipid content*} per Table 20-1.
- Many species can be grown in saline to hypersaline water, thus not competing with agriculture for limited freshwater resources.
- Algae culture systems can be located on marginal and non-arable land, preferably in areas of high solar irradiation and low rainfall, thus not competing with food production.
- The high productivity per unit area means that significantly less land is required compared to other biofuels crops.
- The high productivities also mean a high level of CO_2 capture. Each kilogram of algal biomass fixes about 1.8 kg of CO_2. Algae production systems using open ponds have already been shown to be able to produce an annual average of better than 20 g algae dry biomass m^{-2} day^{-1} (= 131 t CO_2 fixed ha^{-1} $year^{-1}$) which is about the same as sugarcane and significantly higher than most other crops and forestry. The use of algal biofuels is also expected to result in reduced greenhouse gas emissions.

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[1] Metzger, P., Largeau, C. (2005) Botryococcus braunii; a rich source for hydrocarbons and related ether lipids. Applied Microbiology and Biotechnology 66: 486-496.

Figure 20-4 The Cognis Dunaliella salina plant at Hutt Lagoon, Western Australia

(Photo courtesy Prof. Sammy Boussiba).

Figure 20-5 A commercial algae production plant at Ein Yahav, Israel using glass tubular photobioreactors

Using microalgae as a source of renewable fuels is not new and was first proposed in the 1940s. Major research began in the late 1980s in the USA[2] but interest declined once oil prices fell and only resurged recently with increasing oil prices and the need to reduce global CO_2 emissions. This has led to intensive efforts to develop commercially viable processes, especially in the USA[3] but also elsewhere including Australia.

Table 20-1 Lipid productivities of various oil crops[4]

Crop	Lipid productivity (t.ha-1.year-1)
Soybean	0.44
Safflower	0.77
Sunflower	0.95
Rapeseed	1.18
Oil palm	5.89
Microalgae	36.00

20.2 Producing biofuels from algae

When considering the processes for the production of biofuels from algae it is very important to also consider the scale required. For example, in order to produce 100,000 bbl of algae oil per year (equivalent to about 10% of Australia's daily requirement), assuming an annual average biomass productivity of 20 g dry weight m^{-2} d^{-1} and a 30% total lipid content, some 650 ha of ponds and almost 4 GL of water per year are required[5] (this calculation assumes a 100% conversion efficiency of the lipid to biodiesel, a figure which is very unlikely to be achieved). This land area is between 5 and 10 times less that that required for conventional biofuels crops such as sugarcane, oil palm or rapeseed, while the water requirement is about the same[6]. Furthermore, the water does not have to be fresh water.

The production of biofuels from algae involves several steps, the exact details of which are still under development and are likely to vary between different producers and algae species used.

20.2.1 Algae culture

There are two main systems for algal growth (or "culture"). This may be in shallow open ponds, usually of the 'raceway' type or in closed systems called 'photobioreactors'[7]. Raceway ponds are already widely used in commercial microalgae culture around the world and have been shown to be reliable and relatively cheap to construct. Closed photobioreactors are significantly more expensive to construct and operate. They usually need cooling during the day in sunny locations, and they have a much higher energy requirement for circulating the algae culture compared to the paddle wheels used in raceway ponds. At present commercial use of closed photobioreactors is restricted to very high value algae products. However, there are companies working on developing cheaper photobioreactors for production of algal biofuels. Irrespective of the culture system, not all algae species can be grown and different species will be better suited to either one or the other type of system. The potential problem of contamination by other algae and organisms is often cited as a

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[2] Sheehan, J., Dunahay, T., Benemann, J., and Roessler, P.(1998) A look back at the U.S. Department of Energy's Aquatic Species Program - Biodiesel from algae.NREL/TP-580-24190:1-328.

[3] http://www.biofuelsdigest.com/

[4] The algae data are based on work using open ponds at Murdoch University in Perth.

[5] Borowitzka MA, Moheimani NR (2011) Sustainable biofuels from algae. Mitigation and Adaptation Strategies for Global Change.doi:10.1009/s11027-010-9271-9

[6] Data on crop yields and water requirements from FAO (2008) The State of food and agriculture. Biofuels: prospects, risks and opportunities. 128 pp.

[7] Borowitzka M.A. (1999) Commercial production of microalgae: ponds, tanks, tubes and fermenters. Journal of Biotechnology 70: 313-321

limitation to the use of open ponds; however experience has shown that many algae species, especially species growing in saline water, can be grown reliably in open outdoor ponds for very long periods.

The scale of cultivation required to meet biofuel demand means that extremely large quantities of water are required. Therefore algal species growing in saline water are preferred, so as not to compete for limited freshwater resources. The sources of this saline water may be saline groundwater or seawater.

Photosynthetic algae require CO_2 for growth. In order to achieve high productivities it is essential to add CO_2 to the cultures, as diffusion of atmospheric CO_2 into the culture medium is too slow to provide the requirements of dense, rapidly growing algal cultures. Almost any source of CO_2-rich gas can be used, including flue gas from coal or gas-fired power stations, waste gas from cement plants and breweries, and other industrial sources. Because the addition of CO_2 to water causes acidification of the water, the addition of the CO_2-rich gas must be controlled so that the growth medium does not become too acidic for the algae.

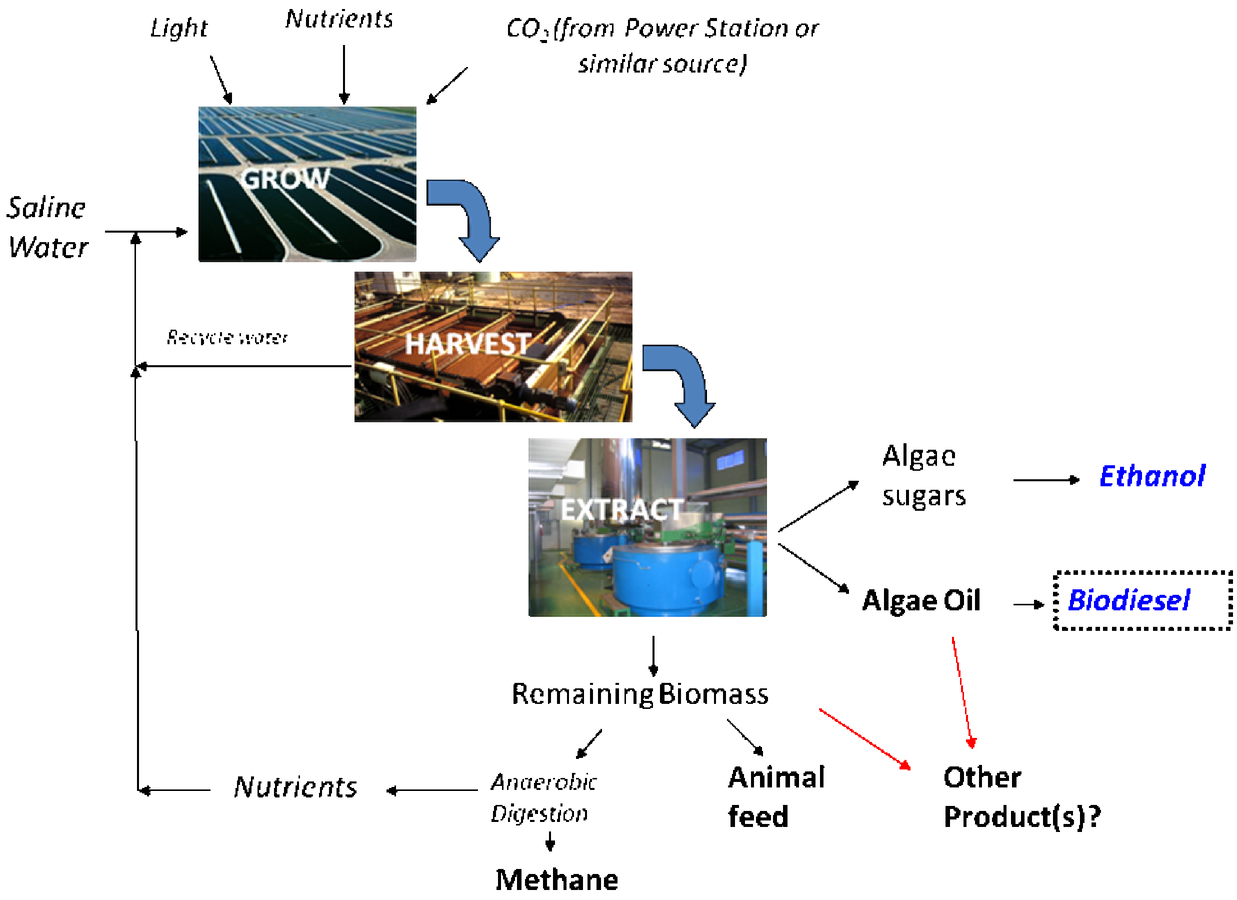

Figure 20-6 Schematic representation of the algae to biofuels production process

Figure 20-7 Raceway ponds at the Earthrise Spirulina plant in California[8]

Figure 20-8 1,000L Tubular photobioreactor (‘Biocoil’) at Murdoch University, Perth, WA

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[8] Each of the ponds in the foreground is about 1 ha in area. (Photo courtesy of Amha Belay)

20.2.2 Harvesting and dewatering

Algae densities in intensive cultures range from 0.3 to 1.0 $g.L^{-1}$ or, in other words, the algae represent less than one thousandth of the culture liquid. This makes harvesting and dewatering a major challenge. The algae are also small (usually between 2 and 30 μm in diameter) and close to neutral buoyancy, meaning that filtration is generally not possible and centrifugation requires too much energy. Thus the options for harvesting algae are limited to various ways of flocculating the algae (i.e. getting the algae to stick together in large groups called ‘flocs’ through the addition of chemicals or by raising the pH) and then recovering them by either flotation or settling. The medium in which the algae are grown also must be recyclable as it still contains valuable nutrients and its disposal would present potential environmental problems and costs. The great variety of algae physical properties means that the harvesting process will be species-specific.

In most cases, the lipid content of the algae must be extracted for the production of biofuels. The extraction step will determine the degree of dewatering required. Drying the algae is possible, but is very likely to require more energy than is contained in the algal biomass.

20.2.3 Extraction and further processing

The oil extraction process will depend on the types of products to be recovered. Because of the prohibitive cost of drying the algae, the extraction step should work using a wet biomass. If only the lipids are to be extracted then solvent extraction with hexane is the most likely process. Alternative extraction processes are being developed, particularly via the use of ‘switchable’ solvents, which change from being hydrophobic (necessary to extract the lipids) to hydrophilic by the addition of CO_2, allowing the extracted oil and solvent to be easily separated [9]. Although many extraction processes are being studied, little information is available as yet on their scalability and their economics at scale.

Liquid fuels can also be produced from microalgal biomass by other processes, such as direct transesterification or by hydrothermal liquefaction. It remains to be seen whether algal biomass can compete with other forms of biomass when whole-of-biomass routes (e.g. hydrothermal or thermochemical) are considered.

20.3 Commercial viability and co-products

Although the production of biofuels such as biodiesel and bioethanol from algae has been technically possible for many years, the cost of production is still too high for commercial applications. Current commercial production costs[10] of algal biomass are greater than \$5 kg^{-1} dry biomass for open pond grown algae and greater than \$35 kg^{-1} for algae grown in closed photobioreactors. In order to produce biofuels this cost must be reduced to less than \$1 kg^{-1} depending on the value of any co-products and the biomass remaining after lipid extraction. To achieve the production cost reduction required all steps (i.e. algal biomass production, harvesting, dewatering and extraction) in the production process must be optimised and be very low cost. The lipid productivity of the algae may also be improved by finding more productive strains or by producing strains with greater photosynthetic efficiency and lipid productivity by mutagenesis or genetic engineering. Reducing costs of production remains THE major challenge for algal biofuels.

One way to improve the economics of the process is to produce other products in addition to the algal oil. The biomass remaining after extraction is rich in proteins and could be used as an animal feed supplement. In theory, the residual algal biomass can be fermented to produce methane for energy generation on-site, and some of the nutrients (especially phosphate) in the biomass can also be recovered to recycle to the algae growth system. It may also be possible to receive some carbon credits for the CO_2 fixed in the process.

There is also great interest in producing other valuable products from the algae. The most commonly cited are the omega-3 and omega-6 fatty acids for use in pharmaceuticals or as a fish oil replacement. Other potential products cited are the carotenoids. However, at this time there is no information as to

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[9] Jessop, P.G. (2011) Searching for green solvents. Green Chemistry 13: 1391-1398

[10] Borowitzka M.A. (1999) Economic evaluation of microalgal processes and products. In: Cohen Z. (ed.), Chemicals from microalgae. Taylor & Francis: London. pp. 387-409

how the recovery of such products will be integrated into the downstream processing of the algal biomass and how this will affect the overall economics. There are questions of competition with non-algae derived sources of these products. There is also the issue of matching the market size for the co-products with large scale algae production for biofuels; algae biofuels have a very large markets and require production of very large quantities of algal biomass, whereas valuable co-products will generally have a limited market size and product values could plummet if there is overproduction.

20.4 Technical and other barriers

The principal technical barriers to commercialization of algal biofuels are the development of integrated harvesting, dewatering and extraction processes able to operate on the very large scale required[11]. These processes will be dependent on the actual algae species being grown, as different algae species vary in some of their physical and chemical properties (i.e. cell density, cell size, nature of cell covering, surface charge etc). The low value of biofuels (relative to algal products currently made commercially) also means that these processes have to be extremely low cost and must have a low energy requirement. This presents major technical challenges.

Another potential barrier is the regulations that might apply to large scale algae culture. This is a very new industry and there is uncertainty at the state and federal level as to whether there may be regulatory issues (e.g., environmental regulations, land use etc.) and which approvals will be needed. Some algae producers are also considering the use of genetically modified (GM) algae strains, but current GM regulations have not considered the biological and ecological characteristics of algae that differ significantly from those of higher plants. The quarantine status of non-indigenous algae strains is also uncertain.

Research and development is required for all stages in the algae oil production process to improve the ultimate economics and to develop processes which can operate at the very large scale required for biofuels production. The algae biofuels R&D effort is supported by the BEAM-RIRDC Algae Biofuels Group[12], a network of researchers, industry and government representatives that supports communication and collaboration between members as well as being a source of information and advice. The group was established with support from the RIRDC.

20.5 Microalgae in Australia

Several Australian companies and research groups are working on developing algal biofuels. Most are still at the R&D stage, although some pilot and demonstration scale facilities have been constructed recently or will be constructed soon. Some details of these are presented here.

(i) Algae.Tec

Algae Tec[13] was listed on the Australian Stock Exchange in January 2011. The company has a patented[14] modular system based on closed photobioreactors contained in 40 foot shipping containers using sunlight captured by solar collectors and transmitted to the algae through an internal illumination system. The company constructed a demonstration plant in NSW in 2012 and has announced plans for another plant in Sri Lanka.

(ii) Aurora Algae

Aurora Algae[15] is a US company located in Perth and Karratha, W.A. In 2011, Aurora Algae opened its first demonstration facility in Karratha in Western Australia. The facility features six open production ponds, each one hectare in size. The location of the facility allows for ample expansion, with the

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[11] Fon Sing S., Isdepsky A., Borowitzka M.A., Moheimani N.R. (2011) Production of biofuels from microalgae. Mitigation and Adaptation Strategies for Global Change. DOI:10.1007/s11027-011-9294-x

[12] http://www.bsb.murdoch.edu.au/groups/beam/BEAM-RIRDC.html
[13] http://algaetec.com.au/
[14] PCT WO 2008/151376 A1
[15] http://www.aurorainc.com/

number of ponds expected to increase. Local industry in the region will supply the carbon dioxide feedstock for the company's algae production.

Aurora Algae is proposing to produce EPA-rich oil and protein-rich biomass products as well as algae-based biodiesel, with initial customers expected to include corporations and industrial facilities in Western Australia.

(iii) Muradel Pty Ltd

Muradel[16] is a joint venture between Murdoch University, the University of South Australia and SQC Pty Ltd. The company was established in 2011 to develop and commercialise the Commonwealth Government funded research ($1.8 million from the Commonwealth and over $2 million from the project partners) on a fully integrated process using elite saline microalgae isolated at Murdoch University over the last 15 years and new harvesting and extraction processes developed at the University of Adelaide for the sustainable production of biofuels. Following two years of outdoor trials in Perth, a one hectare pilot plant was constructed and commissioned in 2010. This pilot plant is located next to the Yurralyi Maya Power Station in Karratha, W.A. to test the process at scale.

(iv) MBD Energy

MBD Energy [17] is focusing on carbon sequestration combined with the production of algal oil and algal meal for livestock feed. The company's Bio-CCS (Bio-based Carbon Capture and Storage) Algal Synthesiser is modular and scalable, and relies on CO_2 supply from CO_2 emitters. MBD has a research agreement with James Cook University and has constructed a 5,000 m^2 R&D facility at James Cook University. Oil extraction technology has been sourced from Origin Oil in the USA. MBD has also built a trial facility at the coal-fired Tarong Power Station in South East Queensland in 2011.

(v) SQC Pty Ltd

SQC Pty Ltd[18] is a South Australian based technology development Company that was established more than ten years ago. The Company's name was derived from the phrase "sequestration of carbon". SQC seeks to develop solutions and commercial applications of innovative technologies involving micro algae. The R&D objectives are to propagate, harvest, and to process microalgae biomass into renewable hydrocarbon products; especially fuels.

In 2004 SQC received funding from the RIRDC for basic research work into microalgae (*Botryococcus* spp) at Flinders University. This was followed in 2007 by a 3 year R&D program, funded jointly by SQC and a Renewable Energy Development Initiative (REDI) grant for research at Flinders University with integrated linkages to R&D work at the company's development laboratory near Port Lincoln in South Australia. SQC is also the commercial partner in a 3-year ARC linkage project involving the University of Adelaide and Flinders University.

The Port Lincoln facility includes a climate-controlled unit where algae bioreactors are being used to grow and study selected algae strains. There are plans are to extend the R&D work to small scale field trials of open-pond algae systems.

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[16] http://muradel.com/
[17] http://www.mbdenergy.com/
[18] http://sqcaustralia.com.au/index.php

Figure 20-9 Algae culture pond at the Aurora Algae Plant, Karratha, WA

Figure 20-10 MBD R&D Facility at James Cook University, Townsville, Qld

Figure 20-11 Murdoch University/University of Adelaide algae biofuels pilot plant in Karratha, WA

(vi) Other Research Activities

Other research groups in Australia working on algae biofuels include the University of Technology Sydney, University of Queensland, Monash University, Flinders University, University of Melbourne, CSIRO and SARDI in South Australia.

20.6 Microalgae overseas

There are over 80 companies in the algae biofuels field overseas. The table below provides an overview of some of the major companies.

Table 20-2 Summary of major overseas companies developing algae biofuels

Company	Location	Process	Current state of activities	Reported or estimated funding (US$)
Synthetic Genomics	California, USA	Open raceway ponds / developing GM algae	R	Exxon Mobil and other funding = $335M
Sapphire Energy	New Mexico, USA	Open raceway ponds (120 ha ponds)	R&D → D	Supported by ARCH Venture Partners, Cascade Investment LLC, the Wellcome Trust, Venrock Partners, US DoE ≈ $205M
Phycal	Cleveland and Hawaii, USA	Open ponds	R&D	≈ $50M
Aurora Algae	USA and Karratha, Australia	Open ponds	R&D → D	≈ $67M
Seambiotic	Ashkelon, Israel	Open raceway pond	R&D → D	?
Aquaflow Bionomics	Marlborough, New Zealand	Not growing but only harvesting	R&D	≈ $5M
Algenol	Mexico and Florida & Texas, USA	Closed photobioreactors / growing algae for producing Bioethanol from hybrid algae	? at pilot stage	≈ $35M
Heliae	Arizona, USA	Plate photobioreactor	R&D	≈ $9M
Solazyme	California, USA	Fermenters / producing oil from algae heterotrophically	R&D → D	≈ $100M
Solix Biofuel	Colorado, USA	Closed photobioreactor/ submerged bags	R&D → D	≈ $36M from several sources

21. Attachment 1: Glossary and abbreviations

<	Less than
>	Greater than
Anhydrous	No water present - for example, anhydrous ethanol is ethanol that has been taken through a final distillation stage or similar process to remove the small amounts of water still present following initial distillation
Arisings	In-forest residues from logging operations
Ash	Inert material in biomass that does undergo energy conversion.
Azeotrope	When the ethanol in an ethanol water mixture is concentrated by distillation the highest concentration of ethanol that can be achieved initially is approximately 96%. At this point the vapour and liquid equilibrium concentrations of ethanol and water are the same, so there is no “driving force” to allow further concentration of the ethanol. To break this azeotrope a further distillation stage is often used, with a third chemical (such as cyclohexane) introduced.
C*	Abbreviation for a sugar with * carbon atoms. Thus a hexose such as glucose is C6, and a pentose such as xylose is C5.
CFB	Circulating Fluidised Bed (gasifier or combustor)
Comminution	The reduction of biomass by mechanical means to obtain a more uniform and valued bulk material.
Coppice	(Verb or noun) As a verb, coppice refers to the ability of a tree species (including many eucalypts) to resprout and regrow from a stump after harvest. As a noun, it usually refers to a stand of trees with coppicing ability.
Corn Stover	The cellulosic residue remaining in the field after the corn cobs are harvested.
Distillation	Distillation is the process of using energy to concentrate one component of a liquid so that it may be progressively separated from other components. In this study it applies to mixtures of ethanol in water, which will leave the fermentation vessel at concentrations of less than 10% ethanol and need to be concentrated to pure ethanol for use as a fuel.
Distillery	Generally taken to mean a plant to produce ethanol from a variety of sugar sources, and includes any feed preparation and the fermentation stage.
Dunder	Common name for the principal residue stream generated from ethanol fermentation and distillation and containing residues from the biomass feed and fermentation products.
e (subscript)	Electrical
E**	Common abbreviation for a blend of ** percent of ethanol in petrol .
Electrolysis	Dissociation of water into hydrogen and oxygen gases using electricity.
Exothermic	A chemical process that give out heat. An example is combustion.
Gallon	Volumetric measure. This report uses US gallons, which are equivalent to 3.785 litres.
GJ	Giga-Joule. A thousand million Joules, the unit of energy. A Joule is a Watt multiplied by a second.
GVW	Gross vehicle weight
HGV	Heavy goods vehicle
HHV	Higher heating value
IEA	International Energy Agency. An Implementing Agreement of IEA is IEA Bioenergy.
LHV	Lower heating value
m.c.	Moisture content. On a wet basis, moisture content is the percentage water in the total biomass, including the mass of moisture. Moisture content may also be expressed on a dry basis. See section 15.2 for detailed explanation.

Miscible	Ability to mix. E.g. ethanol and water are miscible in all proportions.
MSW	Municipal Solid Waste
NOx	Oxides of nitrogen, a pollutant produced during combustion processes. Partially formed from atmospheric oxygen, and partially from the nitrogen in the fuel.
o.d.t.	Oven dry tonne (of biomass)
Oxygenate	A chemical that includes oxygen (such as ethanol) and is added to petrol to increase the overall oxygen level in the fuel.
ppm	Parts per million
RDF	Refuse derived fuel
Saccharide	Sugar, with a polysaccharide being a polymer (or chain) of many sugar molecules.
SCC	Short cycle crop. Also referred to as short rotation coppice (SRC), short rotation forestry (SRF) and plantation energy crops (PEC).
Ton	Measure of mass. In US the short ton is used (2,000 lbs). Approx 909 kg.
Viscosity	Property of a liquid which determines its ability to flow. Honey is for instance more viscous than water. A measure of (kinematic) viscosity is the cS or centiStoke.
Volatile matter	Biomass, when heated to about 400°C to 500°C, gives up a large fraction of its weight in the form of combustible gases. The percentage of volatile matter on a dry basis in biomass typically ranges from 63 percent for rice hulls to over 80 percent for wood. One consequence of high levels of volatiles is that energy may be lost from fuel storage piles, via the loss of volatile organic compounds.

22. Attachment 2: Bioenergy related units

22.1 Units relating to biomass fuels

Biomass fuels vary with plant species (tree genus, crop species), nature of the resource material (straw, wood, bark, leaves, sludge, municipal wastes, algae, manure etc.), and moisture content (from 95% moisture content wet basis) for dairy farm wastes to 10% m.c.(w.b.) for wheat straw. The basic energy value is measured as Joules of energy in 1 kilogram of fuel, (J/kg). For convenience, biomass energy values are normally quoted as MJ/kg or GJ/t.

Since biomass contains varying amounts of water it is also important to specify the **moisture content** when quoting the weight of fuel. For easy comparisons between fuels, this is usually presented as the weight of biomass material as if it was at 0% moisture content (m.c.), when it is termed **tonnes dry matter (tdm)** or **oven dry tonnes (odt).**

Volume. The usual metric unit used for biomass is **cubic metres (m^3).** When individual pieces of biomass are collected together there is always a considerable voidage (volume of air in the spaces between the separate pieces of wood) which is associated with the total observed volume. This makes the simple unit of volume of limited practical use.

Density is normally defined for any object as its weight / volume. Biomass density is sensitive to moisture content, and since biomass varies widely in moisture content as well as material composition, it is more difficult to define. The fundamental measure for biomass is its **basic density**. Taking wood as an example, this is the weight of oven dry wood contained in a unit volume of green wood.

The type and form that the biomass material takes means there can be a considerable difference in the mass of material contained in any given volume. Bulk density (which allows for the density of the material as well as the voidage when the material is being stored or handled) varies with species, piece shape, piece size, and moisture content. It is a useful measure as it affects the amount of biomass fuel that can be carried by a truck or that can be stored on a given area of land alongside a combustion plant. For biomass there is a relationship between bulk density and the moisture content of the material.

Densification. Biomass in small particle forms such as sawdust or shredded municipal green waste can be “densified” to increase the density and enable easier handling and storage. Such **briquettes** or **pellets** can vary from 600kg/m^3 to 1500kg/m^3 actual density depending on the equipment used for densifying the material and the biomass (Figure 22-1). Moisture content usually needs to be between 7 – 14% as if wetter it will not compact easily, as any water present does not compress.

Moisture content The moisture content / dry matter ratio of biomass material varies widely and this has a significant effect on many of the conversion processes. For example the percentage of **solids** present in the digestate affects the biogas yields obtained from an anaerobic digestion process. For dry biomass fuels such as straw or wood, any water present has a considerable effect upon the proportion of the total heat content of the wood that it is possible to recover as a result of combustion systems.

$$\text{Moisture content on a wet basis} = \frac{\textit{weight of moisture present * 100}}{\textit{total weight of biomass}}$$

$$\text{Moisture content on a dry basis} = \frac{\textit{weight of moisture *100}}{\textit{total oven dry weight of biomass}}$$

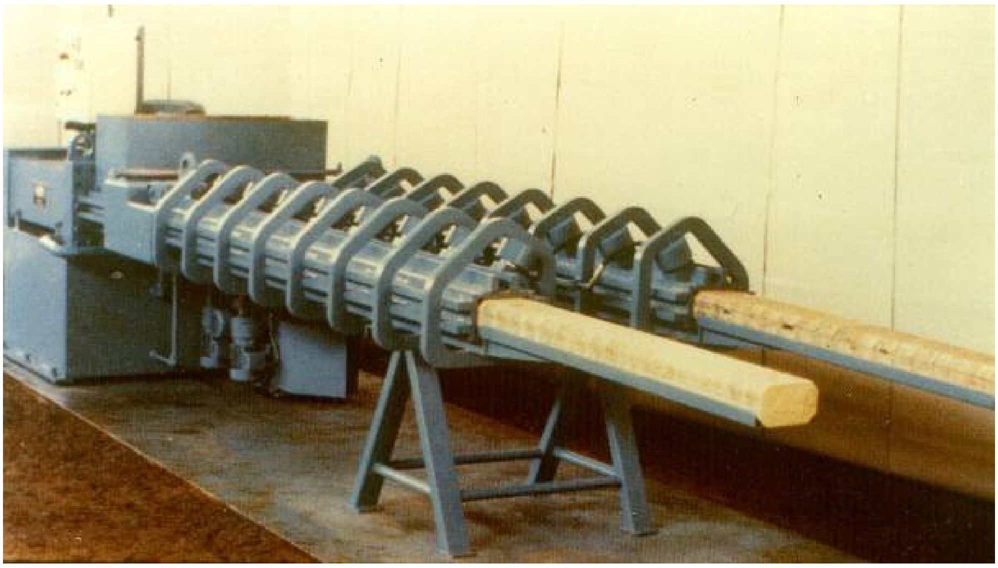

Figure 22-1: Large compacted briquettes of around 1kg each, produced from shredded whole trees

Since energy is derived from biomass fuels by burning, the energy content is the **heat energy** released on combustion in air. It is also termed the **calorific value.** This measure has an upper **gross** value and lower **net** value, the difference being the energy necessary to evaporate the water that is present in the fuel and that formed when the hydrogen in the fuel combines with oxygen during combustion.

22.2 Units relating to bioenergy

For heat and transport fuel applications, **MJ**, **GJ** and **TJ** units are most commonly used. When the biomass is converted into electricity, **kWh**, **MWh** and **GWh** are generally preferred. The **capacity** of a conversion plant is in terms of the maximum output expressed as **kW** or **MW**. When this is in the form of heat the subscript $_{th}$ for "thermal" is added; when as electricity it is as $_e$. Thus a heat plant might have an installed capacity (or nameplate output) of $25MW_{th}$ and a power generating plant of $8MW_e$.

Co-generation is when a plant produces both useful heat and electrical power. It is then also termed a **combined heat and power** plant.

Plant conversion **efficiencies** are generally quoted as overall thermal efficiencies =

$$\frac{\textit{Useful energy output of the conversion plant}}{\textit{energy contained in the biomass fuel}}$$

The physical, chemical and combustion characteristics of biomass fuels can be determined by laboratory test procedures. This information does not need to be carried out for each delivered truck load, but is often useful to determine the value of a resource as feedstock for a power plant. When a power plant is being planned a critical element is to ensure that there is sufficient biomass fuel available in the vicinity for the life of the plant (at least 20 years normally). This means not only assessing the volumes but also the fuel characteristics. Then fuel supply contracts can be negotiated.

The ash content of biomass is generally low at 0.4% to 2.0% by weight (though cereal straw is an exception and can be over 10% due to its relatively high silica content). Higher ash contents of woody biomass can result when poor harvesting and handling methods cause soil contamination of the fuelwood. (Soil consists mainly of non-combustible mineral material that ends up as ash). Ash is a key element of some burners and the lower value can be a problem, not during combustion as such, but for certain designs of moving grate burners, the ash covers the moving surface and protects it from the heat. If the ash content is low, the protection is less and the grate will need to be made of more expensive heat resistant materials.

Variations in heat value are greater with varying moisture content than with biomass type. However, this situation warrants closer examination. Take a pile of green wood chips at 60% m.c. and weighing 1 tonne: 600kg is water and 400kg is dry biomass. The nett energy content is around 8MJ/kg giving a total of 8GJ. If the pile is left to dry to 50% moisture content it loses some weight as the water evaporates off and results in a pile that looks the same, is of similar dimensions and size but now with 400kg dry biomass and only 400kg water. At 50% m.c. it has a heating value of around 10.4 MJ/kg giving 8.3GJ of total energy available for use. Now after some weeks it has dried to 20% m.c. and may have shrunk slightly in volume. It now has 400kg dry matter (though in reality this would have reduced slightly due to respiration losses and some decomposition) and 100kg water so weighs 500kg total. At 17 MJ/kg it has in total 8.5GJ of available energy. So the key point to note is that although the moisture content has dropped the available energy has not increased relatively since the pile has simultaneously become lighter as it dries out.

23. Attachment 3: Standardisation of capital costs

When developing cost estimates for bioenergy plants or other process plants (such as alcohol fuel plants) in Australia at current costs, one source of reference material is studies of similar plants overseas. These data can be useful but must be interpreted with due regard for variations in:

- plant size
- the impact of inflation
- the relative costs at the overseas location and the proposed Australian location.

In his book Process Industry Economics[1], David Brennan of Monash University provides a generalised relationship that shows the impact of these factors:

$$I_p/I_r = (Q_p/Q_r)^b\ (F_p/F_r)\ L$$

Where:

I = fixed capital investment

Q = production capacity of plant

F = inflation index

L = location factor

b = an exponent

p denotes the proposed plant

r denotes the reference plant

23.1 Production capacity

Consider a plant of a known size. Will a plant of identical technology and purpose, but double the capacity, cost twice as much? It will not, but the actual relationship between the two plant costs is largely a function of the different ways in which the increased capacity is achieved. In some cases, larger units of equipment are needed to provide greater capacity; for example larger heat exchangers, pumps, pressure vessels and so on. Doubling the size of a piece of equipment rarely doubles the cost, and this economy of scale is reflected in the overall cost for the larger plant. Alternatively the equipment may not be capable of a doubling in size, and many or all of the items required may need to be duplicated. In this case many costs do double, but general project costs, such as infrastructure and services, engineering and management costs, do not.

These two alternatives are reflected in exponents that are derived from data gained in many instances of process plant construction at different capacities. From this empirical data, Brennan notes that:

- for plants that are increased in capacity by adding streams (ie. duplication rather than expansion), the exponent b is typically 0.8 to 0.9
- for plants that increase capacity while remaining single stream b is lower, typically between 0.5 and 0.6.

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[1] David Brennan - Process Industry Economics. Published by the Institution of Chemical Engineers, Rugby UK, 1998. ISBN 0 85295 391 7

Renewable energy plants are generally single stream overall, even if there are some multiple equipment items such as ethanol fermentation vessels. Single stream methanol plants based on natural gas are built at sizes well above those considered here for biomass to methanol.

23.2 Inflation Index

The process industry monitors the impact of inflation on the cost of plant construction, and regular reports of this impact are available [2]. Thus if the cost of a plant in 2012 is to be estimated from the known cost of a similar plant built in, say 2001, the ratio of the inflation indices for the two years provides a guide of the change in cost. Examples of such cost indices include:

The Chemical Engineering Plant Cost Index for the USA is provided via registration and payment at http://www.che.com/pci/

The Intratec Chemical Plant Construction Index is available at: http://base.intratec.us/home/ic-index

23.3 Location Factors

To convert the price of a plant in the USA or Europe to a plant in Australia involves an analysis of the extent of imported and local equipment in that plant together with an understanding of how prices and productivities for fabrication and construction in Australia compare with those overseas.

Location factors for Australia may be generally considered as:

$$\frac{\text{Cost of plant in Australia (US\$)}}{\text{Cost of equivalent plant in USA (US\$)}}$$

This may be extended to define a conversion factor that includes currency conversion:

$$\frac{\text{Cost of plant in Australia (A\$)}}{\text{Cost of equivalent plant in USA (US\$)}}$$

The capital cost of a process plant includes allowances for equipment and labour (in factories and on site), as well as legislative requirements and so on. Each of these will influence how the cost of a plant in one country may be redeveloped for another country:

The total cost of constructing a processing plant includes cost components for equipment, bulk materials (pipe, cables, concrete etc), construction (labour, management and profit) and engineering/project management costs. These components will vary from project to project, however as a general indication, Humphreys [3] quotes the following split of costs:

labour (construction etc)	33%
equipment and bulk materials	53%
indirect costs and office labour	14%

Of these amounts a proportion of the equipment will not be manufactured in Australia and will be brought from overseas.

Labour – Data published by the US Department of Labor suggest that in 2010 the average hourly cost of labour for Australia was 117% that of the USA [4]. At the same time German rates were estimated at 126% and South Korean rates at 48% of those in the USA.

Materials - Breuer and Brennan [5] considered 1991 data for common process equipment, such as carbon steel pipe, basic pressure vessels and electric pumps, and concluded that at the time there

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[2] See also, for example, the magazines “Chemical Engineering” by McGraw Hill USA, or “Chemical Engineer” by the Institute of Chemical Engineers, Rugby UK.

[3] Humphreys KK - Sources of international cost data - Keynote address at NORDNET 1997 Conference.

[4] http://www.bls.gov/news.release/ichcc.t01.htm

was little cost difference overall between these items in Australia, the UK, or the USA. In 1991 the exchange rate between Australia and the USA was US$1 = A$1.3.

For other items that are not made locally and may make up 20% or more of the equipment and materials for a bioenergy plant, the full overseas cost plus shipping, handling and any agents' fees must be assumed.

As well as the location factors for converting plant costs to Australian sites, there are location factors within Australia that reflect the remoteness of a site, labour availability and so on. Labour costs are considered to have a major impact on cost increases at remote locations, with a 30% premium over capital city rates likely to affect the project cost by some 10% overall. Another impact of building at remote locations is the lack of infrastructure that might be available for city locations, such as power, water, and operational staff. General plant infrastructure, such as product storage and handling may vary significantly between a remote Australian site and an overseas site closer to markets and other infrastructure.

Prices also vary within the USA and Europe, being influenced by all of the same issues described above.

These different perspectives highlight the uncertainties associated with converting overseas plant costs to costs for the same or similar plants in Australia.

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5 Breuer PL, Brennan DJ - Capital cost estimation of process equipment - Institution of Engineers Australia, 1994. ISBN 85825 617 7

24. Attachment 4: The project development pathway

24.1 Summary

The successful development of a commercial bioenergy project will generally involve multiple groups with a diverse range of interests. For instance:

- The feedstock providers may be interested in long term supply agreements at a good price, and on-farm environmental benefits.
- The plant engineer will be interested in reliable, flexible and proven technology, and consistent feed.
- Customers for the bioenergy (as heat, electricity or liquid fuels) will need to know that it is available in appropriate quantities at an agreed price, and meets all relevant quality requirements.
- Project investors will be interested in minimising risks, and attractive and secure financial returns.
- Government bodies will require environmental benefits and a plant that is developed and operated professionally and meets legislative requirements for renewable electricity or fuels.
- Community groups will look for a variety of environmental and community benefits.

When one considers this range of requirements, it is easy to understand that the development of a successful project can be complicated, time consuming and costly. It requires methodical planning, especially to understand and address project risks, demonstrate acceptable financial returns and engage all stakeholders throughout the process. From a technical and financial perspective this is generally achieved through a staged process involving conceptualising the project, conducting prefeasibility and then more detailed feasibility studies, and followed by ‘front end engineering development’ (FEED) to reach an implementation decision. Environmental assessments and approvals, eligibility for renewable energy credits or rebates, and community consultation will proceed in parallel with the technical and cost estimating activities.

The individual components of this development process will be specific to each project, however the general pathway is common not only to bioenergy projects but also to major projects in manufacturing, mining and may other industries. After deciding to proceed, all elements of the project need to be finalised, such as securing feed supplies, all the necessary approvals, contracts for product sales, and equipment procurement, installation and commissioning.

Each of the stages in project development is one part of a logical development pathway. Each stage should reach a successful conclusion to show that further development (at further cost) is warranted.

- Prefeasibility studies involve preliminary assessments of feed supply and cost, markets for products and likely prices, technology selection, approximate plant costings and financial analysis.
- Feasibility studies go into more depth. For instance feed supplies could be characterised through combustion testing, seasonality, cost of setting up the fuel supply chain, sustainability and compliance with regulations, and developing the proposed plan of management and sales. Feasibility studies will also focus on the bioenergy plant, investigating issues such as mass and energy balances, site selection and layout, plant emissions and their control, and plant cost estimates (typically to +/-20 percent accuracy). Sale of electricity, fuels and other products would be investigated. At this stage a more detailed financial analysis would be conducted.
- Front end engineering development (FEED) comprises technical activities to take the project through to finalisation of a document suitable for raising capital for the final design, equipment procurement and construction of the plant. It goes into details such as geotechnical assessment

of the site, equipment lists, piping specifications, health safety and environmental management plans, and noise studies.

- By the completion of the FEED, the biomass supply agreements, major equipment supply contracts, approvals and product purchase agreements should also be understood. It is generally at this point that full project funding may be finalised and implementation of the project can proceed.

24.2 Introduction

How is a successful bioenergy project defined? A successful outcome may be described quite differently by different people, depending on their interest in the project. Here is how a range of different participants might gauge success for a bioenergy project:

- ***Feedstock provider*** – long term supply contract for feed material at a good price, environmental benefits on-farm.
- ***Plant engineer*** – consistent feedstock, reliable technology, good plant utilisation, product quality that consistently meets customer needs.
- ***Customer*** – products (heat, electricity, liquid fuels, co-products) delivered consistently at the agreed price and quality.
- ***Project financier or company shareholder*** – bioenergy plant built for the planned cost and achieves consistent operation and product sales, thus achieving the expected return on investment. Credit for environmental benefits in financial equations to improve project viability. Ability to duplicate the project elsewhere.
- ***Government body*** – cost-effective environmental benefits from a reliable, professionally run project.
- ***Community groups*** – environmental benefits captured, broadening of farm income, long term jobs in the region.

All of these different groups will be involved in most bioenergy projects. The perspective of each different group is quite important, and the outcome of a well developed and operated project should be success for all participants. However, when one considers the range of participants and their various interests and involvement, it is easy to see that the definition and then development of a successful project can be a complicated and time-consuming process.

The costs of planting feed material, establishing optimal harvest and transport procedures and equipment, designing and building a bioenergy plant, and establishing reliable systems to supply product to customers, all mean that most bioenergy projects will require many millions of dollars to implement. To secure this money and to ensure that it is invested sensibly, it is imperative that bioenergy projects are based on sound planning and comprehensive data for every stage of the operation. In particular there are two key points that will enable projects to proceed successfully:

- Understanding risk. This involves knowing where risk or uncertainty occurs at every stage of the operations, and minimising and/or quantifying it. For example, a project may look attractive on initial financial appraisal, but may be based on feed material that has not yet been successfully grown, or on technology that has never been used outside a laboratory or pilot plant. A site may be very suitable for access to feed but result in difficult noise levels for a rural environment. Utilisation of electricity from a bioenergy power plant may be variable, leading to a plant that is often under-utilised and incapable of providing the expected return on investment.
- Demonstrating that the project will make an acceptable financial return. All projects (be they bioenergy or anything else) need to compete for funds, and even the best understood and most environmentally beneficial project will not proceed if it is going to lose money.

Issues relating to the planning, construction and operation of a bioenergy plant are also covered in the IEA report *Bioenergy Project Development and Biomass Supply – Good Practice Guidelines*[1].

24.3 Selecting technology

In the various chapters of this report many options for primary and secondary conversion of biomass to energy have been discussed. The selection of a particular mix of equipment for each project can be a complex task that includes recognition of factors such as:

- Characteristics of the feed, and feed variability on daily, monthly and yearly bases
- The number of different biomass feeds to be utilised over the operating life of the bioenergy plant
- Harvest period for feed, and hence a possible need for dual fuel capability to ensure continuous output, or storage of feed for extended periods when harvesting is not possible
- The size of the project
- Importance of, or interest in, co-products to help make the project financially attractive
- Whether or not the project is linked to another energy, forestry or agricultural enterprise and the long term stability of that enterprise
- The preferred investment strategy of the financiers
- The reliability required by the energy purchaser (for example, is a bioenergy plant supplying electricity into a large electricity grid or is it the sole provider of power at a remote location)
- The timing of the project and returns on investment for forestry and plant
- Whether the project is a “showcase” project of new technology that is unproven at commercial scale but has great potential that may only be developed via a full scale prototype.

While there is great interest in new technologies that seem more efficient than existing processes, it is also possible that these technologies will increase the difficulty of raising capital because of the risk that they will not work as expected, or at all. Also, while a technology may look very attractive at the laboratory scale, taking it from the laboratory, through a pilot stage, to a full scale prototype can involve millions of dollars and years of hard work. This cost and effort may be well worth it, but it must be identified and accepted from the outset when commercially unproven technology is being considered.

Some project teams will have the experience to analyse feeds and make strong judgements about particular aspects of the technology (e.g. combustion grate design, ash handling or noise control). Many, however, will have little experience in these matters. Fortunately there are consultants, equipment suppliers and contractors in Australia and overseas that are experts in particular technologies. It is often easier (and more acceptable to funding bodies) for these experts to be brought into the project early in its development, as designers skilled in particular situations and problems, or perhaps as equipment suppliers that can take total responsibility for the construction, performance and warranties of the bioenergy plant.

24.4 Staged development

The standard method of assessing bioenergy projects is much the same as that for any other large processing plant. Information is gathered and assessed at a certain level of accuracy and cost. A favourable result leads to more detailed assessment and greater accuracy, also at greater cost. Gradually the project is brought to a stage where information is adequate for a commitment of full project funds and a decision to proceed.

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[1] IEA, (2007). Bioenergy project development and biomass supply – good practice guidelines. International Energy Agency OECD/IEA, Paris. 66 pages. http://www.iea.org/textbase/nppdf/free/2007/biomass.pdf

The various stages to reach project approval are outlined below. Details will vary from project to project. The common purpose is to understand and assess the project, working initially with limited funds for this task and progressively spending more on assessment as the project is better understood and remains attractive.

24.4.1 Project conceptualisation

Every bioenergy project starts with an idea. This may be based on an existing or anticipated feed supply, a need for power or energy at a particular location, a community initiative, or energy as a co-product from the processing of biomass for other activities and products. Such an idea is the genesis of a bioenergy project. Using data such as that presented in this report, the proponents can review their idea and add quantities to it. Preliminary discussions with representatives of each major group involved (feed supply, plant construction and operation, product purchase, funding) can test whether the idea is robust enough to progress to the next stage.

24.4.2 Prefeasibility studies

Evaluation of projects that pass the initial criteria for further examination will be subject to a pre-feasibility study, addressing inter alia:

- Feed supply and cost
- Realistic markets and prices for products
- Technology selection
- Plant costing to “order of magnitude” accuracy (± 40%), often based on plant costs from other projects then factored as necessary
- Financial analysis

24.4.3 Feasibility studies

Feasibility studies will compile data to allow a decision by project developers on whether to proceed with full development and project financing. Work will address inter alia:

(i) Feed supply

- Characterisation of each feed, including combustion or other processing tests if necessary
- Quantification of each feed, including seasonal availability and changing availability over the life of the proposed bioenergy plant
- Sustainability characteristics of the feed (including its compliance with any relevant government legislation if renewable energy credits are to be sought.)
- Cost of establishment, harvesting or collection, and transport for each feed
- Availability of equipment and personnel for the supply chain
- Proposed plan for management and sales.

(ii) Bioenergy plant

- Interaction with other businesses (for example a saw mill that could supply feed or use energy)
- Site selection and discussion of reasons behind it
- Preliminary plant layout (site specific)
- Mass and energy balances sufficient to size most equipment, quantify major emissions, and quantify major requirements for bought-in utilities such as water, gas and electricity
- Preliminary emissions study
- Preliminary motor list, with sizes

- Preliminary control system design
- Assessment of alternative options for plant development (for example a turnkey contract for supply and installation, use of second hand equipment, building in stages, etc.)
- Preliminary plant costing, preferably to ±20% accuracy and including site preparation, feed handling, the main bioenergy process, services & utilities, and product handling (e.g. grid connection or biofuel storage). May be based on budget prices for most plant items, with estimated costs for equipment installation, civil works, piping, electrical and control, engineering and project management.

(iii) Products

- Electricity - supply to grid and sales
- Biofuels – supply to existing or new fuel infrastructure and sales
- Genuine markets for any co-products.

(iv) Analysis and reporting

- Detailed description of each aspect of the proposed project
- Capital and operating costs
- Financial analysis (including sensitivity analysis to consider the impacts of changes to major variables such as capital cost, construction time, plant efficiency, feed availability and cost, sales of energy and co-products)
- Program, contracting strategy and timetable for further work.

24.4.4 Front End Engineering Development (FEED)

Also known as a Basic Engineering Package (BEP), the FEED typically comprises the technical activities that take the project through to finalisation of a document suitable for raising capital for design completion, equipment procurement and construction of the plant. It gives the project proponents much of the information they require to allow a decision to proceed. Depending on the size of the project and the nature of equipment supply, this may include:

- Design basis
- Process plant description
- Piping and Instrumentation Diagrams (P&IDs)
- Material and energy balances
- Detailed site survey
- Soil study
- Design climatic conditions
- Plot plans and plant layouts
- Equipment list
- Equipment data sheets (preliminary)
- Sufficient specification of key items for cost estimation by others. Such items might include equipment for handling feed or managing emissions.
- Emission design limits and preliminary estimates
- Piping specifications and line list
- Control strategy
- Preliminary motor list including kW

- Preliminary I/O and instrumentation list
- Details of off-site services
- Interconnection application
- Health, Safety and Environment (H,S & E) management plan requirements
- Environmental referral documentation
- Atmospheric emissions modelling report, and emissions control strategy
- Preliminary noise study
- Fire protection management plan
- List and definition of required items outside battery limits (OBL), in sufficient detail to complete detailed design. OBL items are the project requirements in addition to the main bioenergy units, and may include buildings, other equipment, mobile plant, infrastructure upgrades, etc,
- General project specifications
- Contract management plan
- Tender documents for next stage
- Preliminary plant costing, preferably to ±10% accuracy, based on accurate prices for all major plant items, with quotes or detailed estimates for equipment installation, civil works, piping, electrical and control, engineering and project management.

This work may be carried out by a team that includes the developer, technical consultants, equipment suppliers and construction contractors. The exact split of work will depend on the specific requirements for each project.

24.4.5 Implementation decision

The completion of a FEED package should provide the project developer with capital and operating cost estimates that are of sufficient accuracy to support a decision to proceed with project financing and implementation. There are other elements to the project that must also be suitably developed before project implementation. These may include:

Feed supply – agreement(s) for supply of feed, which may include quantities, physical characteristics and composition, delivery arrangements, timing etc.

Equipment supply – it may be appropriate to enter into an agreement with a contractor or an equipment supplier for a “turnkey” package. This could involve the supplier taking responsibility for most of the equipment on the site, including feed handling, energy conversion, product handling and waste management. One of the benefits of such an approach is that the supplier may offer a fixed price, and a warranty or performance guarantee (e.g. for an agreed feed the plant will produce an agreed energy output with agreed operating costs, emissions, hours of operation per year, and so on). Such guarantees can be very useful in fundraising.

Alternatively the project developers may decide to place several orders for packages of equipment, or even purchase individual items and assemble the plant themselves.

Approvals – A variety of approvals are required for the construction and operation of large processing facilities, and bioenergy plants are no exception. While some of these approvals may not be finalised until well into the process of detailed design, they must be understood and examined during the time leading up to an implementation decision. These approvals will vary from project to project but may include liaison with:

- local council
- environment protection authority
- fire department
- water supply authority
- state government
- electricity supply authority.

Product purchase agreement – The project can not expect funding and implementation without a clear indication of who will buy the product (e.g. electricity or transport fuel) and under what conditions the purchase will take place. It is expected that a product purchase agreement will be developed and signed (perhaps with conditions precedent) at this stage.