



An Australian Government Initiative



Six best bet products from agroforestry biomass grown in low rainfall areas

**A report for the RIRDC/Land & Water
Australia/FWPRDC/MDBC
Joint Venture Agroforestry Program**

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Foreword

Salinity and land degradation are major threats to the sustainability of Australia's rural economy and society. A potential solution to some of the salinity issues is to plant woody vegetation in the drier areas to lower the water table and draw the saline water back down into the soil profile, where it cannot affect rural productivity. However, woody vegetation is unlikely to be planted on the scale required to achieve these environmental outcomes unless there is an economic driver guiding this planting.

This project investigated the markets and prospects for six products that may be produced from low rainfall grown woody biomass. The products selected were: appearance grade timber, dry formed fibreboard, wood-plastic composites, electricity from woody biomass, alcohols – ethanol and methanol, and pyrolytic bio-oil. The project reviewed the markets and product prospects between 2001 and 2003. The report also reviews product use and processing and manufacturing technology, and estimates the planted resource required to service processing plants. The study concluded that wood raw material costs will be crucial to the economic viability of the production processes in a low rainfall environment. Production and supply of woody feedstock is currently not cheap enough in low rainfall regions to compete with either similar feedstocks grown in higher rainfall regions, or fossil fuel feedstocks. The report recommends that future R&D efforts are focused on improving the germplasm and silviculture of promising woody perennials, as well as novel harvesting approaches, in order to improve the quality and yield of feedstocks and significantly reduce the delivered cost of raw materials to a competitive and attractive level.

The report is a benchmark study on the status of low rainfall product and market development at the time. A second, subsequent report from this project presents an economic framework for assessing potential markets for these products, for low rainfall regions. Current projects are re-evaluating industry feasibility and product options at a regional and national level, taking into account the impact of increased drivers for carbon offsets, bioenergy production, and environmental services within Australia, as well as the potential for developing regionally-based industries based on integrated products. Those studies will use this report as a reference.

This project was funded by the Joint Venture Agroforestry Program (JVAP), which is supported by three R&D Corporations — Rural Industries Research and Development Corporation (RIRDC), Land & Water Australia, and Forest and Wood Products Research and Development Corporation (FWPRDC), together with the Murray-Darling Basin Commission (MDBC). The R&D Corporations are funded principally by the Australian Government. State and Australian Governments contribute funds to the MDBC.

This report, a new addition to RIRDC's diverse range of over 1600 research publications, forms part of our Agroforestry and Farm Forestry R&D program, which aims to integrate sustainable and productive agroforestry within Australian farming systems.

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Abbreviations

ABARE	Australian Bureau of Agricultural and Resource Economics
AFFA	Agriculture Fisheries and Forestry Australia
AFG	Australian Forest Growers
AGO	Australian Greenhouse Office
CALM	Conservation and Land Management
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DNRE	Department of Natural Resources and Environment (Victoria)
EA	Environment Australia
FFP	Forestry and Forest Products
FR	fire resistant
HDF	high density fibreboard
HDPE	high density polyethylene
JVAP	Joint Venture Agroforestry Program
LVL	laminated veneer lumber
LDF	low density fibreboard
LDPE	low density polyethylene
LHV	low heating value
MAI	mean annual increment
MDBC	Murray Darling Basin Commission
MDF	medium density fibreboard
MDI	Methylene Diphenylene Diisocyanate MR moisture resistant
MRET	Mandatory Renewable Energy Target
MUF	melamine urea formaldehyde
NAFI	National Association of Forest Industries
OD	oven dry
PF	phenol formaldehyde
PP	polypropylene
PS	polystyrene
PVA	polyvinyl acetate
PVC	polyvinyl chloride
RIRDC	Rural Industries Research and Development Corporation
SFNSW	State Forests New South Wales
UF	urea formaldehyde
WPC	wood-plastic composite

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Executive Summary

What the report is about

This report reviews the potential market size and prospects for six selected products that may be produced from low rainfall grown woody biomass. Markets and product prospects were assessed between 2001 and 2003. The report also reviews product use and processing technology for the products, and estimates the planted resource required to service viable processing plants in the region. This is a benchmark study for future assessments of product and market development for low rainfall regions.

Who is the report targeted at?

The report is for industry and government considering options for salinity amelioration and agroforestry development in low to medium rainfall regions of Australia. It also provides useful context for farm foresters and researchers involved in development of products and production systems.

Background

Salinity and land degradation are major threats to the sustainability of Australia's rural economy and society. A potential solution to some of the salinity issues is to plant woody vegetation in the drier areas to lower the water table and draw the saline water back down into the soil profile, where it cannot affect rural productivity. However, woody vegetation is unlikely to be planted on the scale required to achieve these environmental outcomes unless there is an economic driver guiding this planting. In low to medium rainfall zones where dryland salinity is most prevalent, growth rates of trees are slower, and there can be large transport distances to coastal ports and processing facilities.

Aims/Objectives

The main aim was to broadly assess the economic viability of six target products / processing systems, based on woody biomass feed-stocks grown in low rainfall regions of Australia.

Methods used

The products were selected by a committee comprised of representatives from RIRDC / JVAP, AFFA-Farm Forestry, Primary Industries SA, CALM-WA, SFNSW, DNRE-Private Forestry, MDBC, AGO, AFG, EA, ABARE, NAFI and CSIRO Forestry and Forest Products. The products selected for investigation were:

- appearance grade timber
- dry formed fibreboard
- wood-plastic composites
- electricity from woody biomass
- alcohols – ethanol and methanol
- pyrolytic bio-oil.

The above products fall into two distinct groups. Appearance grade timber, fibreboard and wood plastic composites are encompassed within the traditional or emerging forest products industries. The remaining products are concerned with the energy and chemicals industries which are large, challenging markets currently dominated by fossil fuels and synthetic chemicals.

Results and implications for stakeholders:

Appearance grade timber

Hardwoods grown in low rainfall areas would have suitable properties for the non-structural sawnwood and veneer market. Predictions are that the market for sawn timber will decline gradually to the year 2010, and thereafter increase to around 1.3 million m³ / annum. In the future, the market will be dominated by appearance grade products. A potentially sizeable market for appearance grade products also exists in Japan, though careful selection of appropriate timbers would be required to realise significant market penetration. On the other hand, significant expansion in hardwood plantation resources and associated processing industries is anticipated in other parts of Asia. This could have a significant impact not only on the shape and composition of overseas markets, but also the domestic Australian market. The extent of the expansion of hardwood plantations in higher rainfall regions across Australia will also be a factor in determining the future for low rainfall grown hardwoods.

It is believed that any sawmill constructed to process low rainfall grown timbers would need to have a minimum input capacity of 30,000 m³ / annum of logs in order to be economically viable. Such a mill would require around 20,000 hectares of forest to provide the necessary feedstock.

The key drawback to establishing an economically viable industry is that current hardwood growth rates in low rainfall areas are believed to be too low. Accordingly, advances will need to be realised in the following areas: genetic improvements to increase growth rate, form and branching habit; improved silvicultural management to produce larger diameter stems; drying strategies and schedules developed and optimised for low rainfall species; improved understanding of gluing, machining and stability attributes. Furthermore, markets will need to be found for sawing residues and small roundwood.

It has also been suggested that costs could be markedly reduced if mill capacities and the level of technical sophistication were significantly increased. However, it is uncertain whether such approaches would be viable for processing hardwoods grown in dispersed lots in low rainfall regions.

It is believed that penetration and capture of markets equating to around half of the current domestic Australian market for non-structural hardwood timbers by low rainfall grown appearance products is probably optimistic. In such a scenario, the land area required for a sustainable plantation-based industry would probably amount to less than 1% of the 80 million hectares in salinity-prone agricultural regions in Australia. However, this would still be an industry of significant size. For example, if suitable, the sawing residues and small roundwood from such an industry would be sufficient to supply a dry formed fibreboard industry at least twice the size of the current Australian industry.

Dry formed fibreboard

A substantial future potential export market exists for Australian produced MDF in the Asia-Pacific region. However, likely strong competition from other producers in the region i.e. New Zealand, South East Asia, based on low-cost high rainfall grown resources, and possibly also recycled wood and agri-residues, will severely limit potential market sizes. It is suggested that a realistic goal for any future low rainfall zone MDF industry is probably around 10% market penetration, which would require approximately 500,000 ha of plantation area in order to sustain it, i.e. 0.6% of the total area of agricultural land in the salinity zone. In order to realise such a goal, substantial R&D efforts will be required to develop radical new approaches to generating low cost woody biomass with the appropriate properties.

Wood-plastic composites

Wood-plastic composites (WPCs) are new products which have shown strong growth in recent years in North America; sales of WPCs exceeded 300,000 tonnes in 2000, and the market is predicted to double in size by 2005. WPCs are used in a variety of applications, primarily windows, decking, siding, cladding, mouldings and architrave, and directly substitute materials made from either wood or plastic alone. Compared with wood-based materials they offer improved dimensional stability and resistance to biodegradation. In the case of plastics they offer potential cost savings.

It is believed that WPCs represent a potential option for utilising woody biomass grown in low rainfall areas of Australia. In terms of value, potentially sizeable domestic and export markets exist for the products. The WPC industry in Australia is currently in its infancy. It is estimated that a market size of 50,000 tonnes per annum of product could exist in 2010, with a value of AU\$200 million. The drawback is that when viewed in isolation, the planted land area required to provide the wood feedstock for such an industry would be negligible in the context of the total land area in the salinity zone. However, the relatively small scale of production units, the modest associated investment costs, and the fact that residues from (low rainfall) saw-milling operations might be suitable are attractive features of WPCs.

In order to fully evaluate the prospects for a low rainfall based WPC industry, further work is required to determine the likely performance of the products in Australian and other sub-tropical environments. Work is also required to determine the relative suitability of woody residues from low rainfall regions for WPCs compared with residues derived from high rainfall based operations and urban environments e.g. recycled wood.

Electricity from biomass

Annual consumption of electricity in Australia is around 200,000 GWh, and this is predicted to grow at about 2% / annum for the foreseeable future. Eighty five percent of Australia's electricity is generated by the combustion of coal. The remainder comes predominantly from the combustion of gas and hydropower. The latter currently represents the key source of Australia's renewable electricity. In 2003, the mean production cost of electricity from coal was around AU\$0.03 / kWh.

A variety of methods exist for the generation of electricity from biomass. Of these, co-generation (combustion with coal in existing power stations) and gasification appear to offer the most promise at present. The benefits of the former are the savings in capital costs, whilst the latter offers potential efficiency improvements. However, even when the biomass is available at near zero cost, with current technology it is not feasible to generate and supply electricity at a similar cost to that of the coal-based industry. Biomass-based plants must be necessarily smaller in capacity due to the greater costs associated with transporting biomass. They are consequently less efficient and both their fixed and variable costs are higher. The relatively high moisture content of biomass and its impact on efficiency is also a drawback.

The Australian Government's % Mandatory Renewable Energy Target (MRET) offers a potential mechanism for the establishment of a biomass-based industry, particularly where biomass has cost advantages over other forms of renewable energy e.g. wind and solar. Although an 'anomaly' in the MRET legislation prevents plantations being established solely for bioenergy production, it is believed that for the foreseeable future any biomass-based electricity generation is in any case likely to be based on various waste streams from a variety of industries e.g. forestry and agriculture. This is because of the likely lower cost of such feed-stocks. Opportunities for large-scale plantings in low rainfall areas aimed solely at providing feed-stocks for the electricity generating market, thus appear to be limited. Residues from low rainfall crops could have more potential as a feedstock. However, in this case the potential size of any electricity generating industry would effectively be limited by the size of any other low rainfall industries based on the primary feed-stocks.

The high costs associated with servicing the electricity needs of the rural areas of Australia offer one possible opportunity for low rainfall grown biomass. In this case small-scale biomass-based electricity generating plants could be economically viable. Such plants might typically have generating capacities of around 1 MW with annual inputs of around 10,000 tonnes of dry biomass. However, the utilisation of low cost residues would still probably be necessary in order to make this an attractive option; this is likely to be true even without the current MRET anomaly. Given this, other viable industries based on woody biomass would still need to be established.

Alcohols - ethanol and methanol

Ethanol can be produced from woody biomass and can be used as a substitute liquid fuel for gasoline. As such, the domestic (and indeed export) market for ethanol derived from woody biomass is potentially very large. However, processing technology has not yet been proven which can convert woody biomass to ethanol, such that the latter can compete on a straight economic basis with gasoline. The large variation in estimated production costs stems from differences in scale of operation, type and cost of feedstock and the proposed processing technology. Significantly, the lower estimated costs are associated with the larger operations, with assumed low feedstock costs and high biomass to ethanol conversion ratios using largely unproven technology.

It has been estimated that the minimum size of ethanol plant, which could be economically viable, would have an output capacity of around 50 million litres / annum, and raw material input requirements of 165,000 tonnes / annum of dry biomass. The planted area in low rainfall regions required to sustain such an industry could range from 100,000 to 1 million hectares, depending on achievable growth rates, and the range and type of competing / synergistic industries in the same region. A low rainfall ethanol industry could thus have a significant effect on salinity.

However, for this to become a reality, a number of further developments will be required. Firstly, efficient and proven methods for the conversion of pentose sugars to ethanol need to be found. The identification of viable markets for by-products would also significantly reduce costs. These latter requirements apply equally to all potential ethanol initiatives. From a low rainfall perspective, approaches will also need to be found which facilitate the production of biomass at very low unit cost and possibly also with tailored properties e.g. high cellulose contents.

Much of the methanol currently produced in the world is used for the production of other chemicals e.g. formaldehyde, for use in thermosetting adhesives. However, similarly to ethanol, methanol can be used as a substitute liquid fuel for gasoline. It also has the potential to be used in fuel cells, a technology which is currently being developed and assessed for vehicles of the future. Consequently, potentially very large markets exist for methanol. Methanol is currently produced from natural gas. However, it can also be derived from woody biomass (this is not a new concept; methanol is often referred to as 'wood alcohol' in many text books).

Traditional methods of producing methanol from wood only give yields of around 1-2%. However, it is possible to increase yields to over 30% by the conversion of the biomass to "synthesis gas" via gasification, followed by catalytic conversion to methanol. Further hydrogen is required to be fed into the synthesis gas to convert as much of the biomass carbon as possible to methanol carbon. One process, the so-called HYNOL process, is claimed to be able to produce methanol at a cost which is competitive with gasoline e.g. of AU\$0.22 / litre. However, the scale of processing plant required is large, having an annual output capacity of over 4,000 million litres of methanol and an annual input of around 1.6 million tonnes of dry woody biomass. It is estimated that an individual plant would require planted areas in low rainfall regions well in excess of 1 million hectares in order to service its feedstock requirements. However, the haulage costs alone for such an operation could be prohibitive if the planted areas were widely dispersed. Its suitability for low rainfall regions must therefore be highly questionable.

Pyrolytic bio-oil

Pyrolytic bio-oil is the liquid that is produced from various pyrolytic treatments of woody materials. Bio-oil typically consists of a complex mixture of organic compounds, with the precise composition varying with both the feedstock and pyrolysis process used. Fast (or flash) pyrolysis methods are used to maximise the yield, which can be as high as 80% (by mass on the original mass of oven dry wood).

Bio-oil has a number of potential uses, including: a fuel for electricity generation; transport fuels; a source of value-added chemical compounds e.g. for the speciality chemicals, food flavourings, pharmaceuticals, adhesives and wood preservation industries. To date most attention has been focused on its potential as a fuel for electricity generation. It has apparently been utilised for a number of years in at least one coal-fired electricity generating plant in Canada. Despite this, however, bio-oil is still largely at the pilot scale of its development process, with the merits of at least three technologies currently being evaluated by various research groups around the world. One drawback of bio-oil is that it has less than half of the fuel energy content of petrochemical fuels, owing to its high water and oxygen content. Technology exists to upgrade bio-oil to transport grade fuel, but it is too expensive to be competitive with petrochemically derived diesel. Similarly, whilst bio-oil has been shown to be comprised of a large number of value-added compounds, technology has yet to be identified to facilitate their economic separation.

It is believed that whilst a low rainfall industry based on small-scale biomass pyrolysis units has many attractions, research into the following is required in order to make it a reality: optimisation of the pyrolysis process; evaluation of the influence of raw material type on process economics and bio-oil composition; technologies to economically upgrade bio-oil to transport grade fuel and to fractionate bio-oil into pure value added compounds.

Conclusions

Table 1 summarises estimated production cost data and feedstock requirements for 'typical' production facilities for each of the target products analysed in this review.

Table 1: Summary of key production cost data and feedstock requirements for target products (based on 2003 data)

Product	Total Production Cost*	Raw material requirements for a typical production facility (annual)**
Appearance grade timber	AU\$320 - AU\$610 / m ³	30,000 m ³
MDF	AU\$205 / m ³	75,000 tonnes
Electricity from biomass	AU\$0.05 / kWh	10,000 tonnes
Ethanol	AU\$0.31 - AU\$1.50 / litre	165,000 tonnes
Methanol	AU\$0.18 / litre	1.6 million tonnes
HDPE Wood Plastic Composite	AU\$900 - AU\$2050/tonne	5,000 tonnes
Electricity from Pyrolytic bio-oil	AU\$0.15 / kWh	40,000 tonnes

*Excluding wood / biomass raw material cost

**Mass values are for oven dry material

The estimated production costs for target products are exclusive of wood raw material costs, and it is believed that they are not likely to vary significantly between different (rainfall) regions. The wood raw material costs will thus be crucial to the economic viability of the production processes in a low rainfall environment. Evidence suggests that currently it is probably not possible to produce and supply woody feedstock cheaply enough in low rainfall regions to compete with either similar feedstocks grown in higher rainfall regions or fossil fuel feedstocks. This suggests that future R&D efforts should be predominantly focused on improving the germplasm and silviculture of selected, promising woody perennials, as well as novel harvesting approaches, in order to improve the quality and yield of feedstocks and significantly reduce the delivered cost of raw materials to a competitive and attractive level.

Introduction

Dryland salinity is a serious problem affecting many environmental systems and economic activities in significant areas of Australia. It is generally accepted that no single land-use option or strategy will halt the spread of salinity. Instead, a number of integrated solutions are envisaged, including (Stirzaker *et al*, 2000):

- commercially driven tree production systems
- new farming systems comprised of novel mixes of annual and perennial plants
- new forms of cereals, pulses, oilseeds and forages
- refined land assessment tools that optimise farm planning to meet water quantity and quality goals
- new tools for land managers to monitor leakage past the root zone.

This report focuses primarily on the first two of the above suggested solutions, with the main aim being to broadly assess the economic viability of six target products / processing systems, based on woody biomass feed-stocks grown in low rainfall regions of Australia. The market and product prospects were assessed between 2001 and 2003.

Tickle *et al* (2001) recently estimated that the area of cleared agricultural land which would be suitable for commercial timber plantations to be around 5.5 million hectares, or 6.4% of the 80 million hectares of agricultural land on which dryland salinity is a relevant land management issue. (Note that within this total area, only a proportion is already directly affected or is projected to be directly affected by salinity (variously estimated from a few percent to 30 percent in different regions and catchments). However, modifications to land management practices are required over a larger proportion of this total area to ameliorate or prevent off-site salinity damage such as rising salt levels in rivers and degradation of remnant native vegetation).

Tickle *et al* (2001) further suggested that conventional commercial timber production would only have a relatively small role in the overall control of dryland salinity, as often the areas suitable for commercial timber production do not overlap with those areas posing the greatest salinity hazard. Tickle *et al* (2001) proposed that any areas with less than 600mm annual rainfall were unlikely to be suitable for commercial timber production. This seems reasonable, given that Blakemore *et al* (2001) estimated that mean annual increments (MAI) for some unmanaged stands of trees in the 400–600 mm rainfall zone ranged between 1.3 – 5.0 m³ / ha / yr. This in itself is a very low level of productivity by conventional commercial tree growing standards in higher rainfall regions, where 15 m³ / ha / yr is regarded as a low productivity site. Indeed, the low yields of woody biomass that are likely to accrue from conventional forestry approaches in lower rainfall areas has led some people to argue that radical new systems of woody biomass production will be required if any new ventures of a significant scale are to succeed (Bartle, 2001).

From the above it is clear that developing viable commercial products and processes based on woody biomass grown in drier areas (400-600 mm rainfall zones) will be challenging. As an initial step in this process, the Joint Venture Agricultural Program (JVAP) elected to fund a basic analysis of six selected products / processes which could potentially be based on woody biomass grown in low rainfall areas.

The process of selecting which six 'best bet' products to analyse was itself a challenge. The excellent review on potential commercial prospects in agroforestry conducted by Zorzetto and Chudleigh (1999), in which virtually all conceivable prospects were highlighted, formed the basis for narrowing down the selection. However, a key difficulty still was that there is a range of criteria which are clearly important in determining product / process suitability, but that the criteria are not necessarily synergistic and often difficult to quantify. Some examples of key selection criteria include potential market sizes for products, likelihood of market penetration, extent of alignment with conventional forestry practices and forest products industries, R&D investment requirements and likely salinity,

carbon and biodiversity benefits. Given all of these, it is very difficult to pick obvious front runners. For example, Bartle (2001) reviewed many of these issues in the context of the ongoing mallee eucalypt initiatives in Western Australia, and concluded that unless the potential markets for products were likely to be large, the resulting benefits to farmers (and the environment) would be negligible. Whilst the logic of this argument is inescapable, the resulting products and processes which fit such a selection criterion are more often than not very high risk in nature, requiring substantial R&D inputs with no guarantee of successful outcomes. It might also be argued that the 'on-site' biodiversity benefits of such ventures could be modest, because they are likely to involve the large-scale farming of mono-cultures. Certainly, direct biodiversity benefits will be very variable, being dependent upon the species used, the management practices employed and the form of land management being replaced. Furthermore, indirect biodiversity benefits could actually be very significant, for example as a result of increased water usage leading to improvements in water quality and reduced salt damage to native vegetation and wildlife.

In order to facilitate the selection of target products and processes, advice was sought from a committee of experienced representatives drawn from a number of organisations, including RIRDC / JVAP, AFFA-Farm Forestry, Primary Industries SA, CALM-WA, SFNSW, DNRE-Private Forestry, MDBC, AGO, AFG, EA, ABARE, NAFI and CSIRO Forestry and Forest Products. Four target products were selected by the committee; the remaining two products were selected by the authors after further extensive consultation.

The products selected for investigation fell into two distinct groups (see Table 2). One group was aligned to the existing forest products industry, whilst the other concerned the energy and chemicals industries which, whilst potentially very large, are challenging markets which are currently dominated by fossil fuels and synthetic chemicals.

Table 2: Target products selected for investigation

Forest Products	Energy and Chemicals
Appearance grade timber	Electricity from woody biomass
Dry formed fibreboard	Alcohols – ethanol and methanol
Wood-plastic composites	Bio-oil from wood pyrolysis

The rationale for the selection of the six products was as follows. Appearance grade timber was selected on the basis that to date, and for the immediate future, revegetation of low rainfall areas will be dominated by conventional forestry approaches. Sawlogs from hardwoods grown in these areas are likely to be too high density for structural lumber, but ideally suited for appearance grade timbers. The dry formed fibreboard industry is still relatively young, with good future growth prospects. The products can potentially be manufactured from a wide range of woody / lignocellulosic raw materials, unlike most other panel products. Wood plastic composites are a new family of composite materials which are currently exhibiting strong growth in North America. Similarly to dry formed fibreboard, the products can potentially be manufactured from a wide range of woody materials. The products and processes concerning energy and chemicals were selected primarily on the basis of potential market sizes. Significant penetration of the markets would require vast quantities of woody biomass feed-stocks.

For the two product groups it is clear that different challenges will need to be overcome if significant industries are to be established based on woody biomass feed-stocks from low rainfall areas. For the forest products, the main challenges will be provided by the competition from conventional forest operations based on more productive, higher rainfall operations. However, much greater challenges are faced within the sphere of energy and chemicals. Dry zone woody feed-stocks will not only have to compete with their higher rainfall counterparts, but also other naturally derived raw materials (e.g. starch and sugar) and fossil fuels.

Appearance grade timber

Introduction

Trees grown in low rainfall areas are likely to produce small diameter stems of higher density timber, with relatively poor form at relatively slow growth rates, compared to high rainfall plantations and native forests. It is unlikely, therefore, that they will be suitable for the production of commodity structural lumber, based on either quality or price. However, low rainfall plantings of appropriate Eucalypt species have the potential to yield timbers with attractive features and appealing colours suitable for the higher value appearance market. It is expected that both form and growth rate aspects of trees will be enhanced with the introduction of genetically improved planting stock from programs such as the Australian Low Rainfall Tree Improvement Group (ALRTIG). However, these appearance products grown in the low rainfall areas will still have to compete successfully with similar products grown and produced in higher rainfall areas.

Appearance products are generally used for decorative purposes. Products include flooring, decorative wood panels, timber components of furniture, benches and table tops and unpainted joinery. Appearance timber products differ from structural timber products in that there is generally no significant load-bearing requirement, and thus they can comprise smaller and thinner components. Appearance timber products generally have a higher value than structural timber, but the cost to produce this higher value is greater. Keeping sawing and drying costs to a minimum will therefore be necessary in order to upgrade the initial sawn timber to produce value added appearance products.

The low rainfall resource is likely to be much more dispersed than higher-rainfall species, necessitating lower throughput facilities in order to acquire timber input from within a reasonable haulage distance. The use of multiple saw technology is likely to be necessary to handle high growth stresses and to achieve a level of productivity, combined with appropriate drying and further processing technologies, to ensure final products are competitively priced to the end-user.



Figure 1: 10-year-old *E. cladocalyx*, 400 mm natural rain-fed (from Waugh and Washusen 2000)

As with all sawing processes, markets for the residues (slabwood, sawdust etc.) from the log conversion process will be important. The higher density of the resource may preclude the use of the residues for Kraft pulp. However, they may well be suitable for a range of other uses, including many of the other target products selected for review in this work e.g. fibreboard, energy, wood fibre plastics and bio-oil.

The advantages of timbers grown in the low rainfall area compared to the high rainfall area lie in their natural feature beauty and likely higher durability. This offers opportunities for these products to be used in more exposed environments such as decking or outdoor furniture, where the competing products would be jarrah and imported, durable hardwoods.

Markets

The world-wide market for appearance grade timbers is not easily quantified. This is largely due to the tendency to quote production and consumption figures for sawnwood in general; differentiation into structural and appearance grades rarely occurs. The world consumption of sawnwood (including softwood, hardwood and structural wood) is predicted to grow at a modest annual rate of around 1% over the next decade (ABARE, 2002). Consumption in 1996 was estimated at 430 million m³, and is expected to increase to around 500 million m³ in 2010.

Australia

Consumption of hardwood sawnwood in Australia has been declining steadily over the last 20 years (URS Forestry and Ausnewz, 2002), from above 2 million m³ in 1985 to 1.13 million m³ in 2002 (ABARE, 2002). Over the last decade, hardwood consumption has declined by an average of 2.4% per annum. The fall in consumption has been caused primarily by substitution with softwood sawnwood in the construction industry, with sawn softwood now accounting for more than three quarters of the total Australian sawn timber market. A steady reduction in the native hardwood forest area available for logging has also been a contributing factor to the decline in sawn hardwood consumption.

Australia produced 1.10 million m³ of sawn hardwood in 2001–2002, of which around 80,000 m³ was exported (ABARE, 2002). In the same period, Australia imported approximately 108,000 m³ of dressed and rough sawn hardwood timber, primarily from Indonesia, Malaysia and Fiji, with an estimated value of AU\$102 million. It is believed that the imported material was almost exclusively appearance grade. This may well be a market opportunity for low rainfall grown timbers, as there could be an opportunity for substitution of some imported timbers, though it is unlikely that the entire import volume would be eliminated, as demand is likely to remain for some niche products.

Over the last 15 years the Australian hardwood sawnwood industry has responded to the changing market environment by re-focusing its product ranges. In 1985 as much as 60% of production was targeted at the construction market, with a further 30% destined for pallets and palings. Much of this production was green and rough sawn. In contrast, it is estimated that by 2000 over 50% of output was targeted at the appearance grade and flooring markets, with increasing emphasis on kiln drying and value adding. It is anticipated that these trends will continue, and that in the future the bulk of the sawn hardwood consumed in Australia will be in appearance grade applications.

It is predicted that consumption of hardwood sawnwood will continue to decline very gradually to around 2010, and will then increase as significant supplies of re-growth hardwood sawlogs and possibly also plantation sawlogs become available. Beyond 2010 it is believed that hardwood sawnwood consumption in Australia will be around 1.3 million m³ per annum.

North America

Beall (2000) indicates that the North American hardwood market will be difficult to enter, and establishing a market for low rainfall produced eucalypts requires a consistent supply of timber with known processing properties and consistent product quality control. It is likely that only higher grades of imported hardwoods and “feature” wood will compete successfully in the North American market, although the world push to reduce reliance on rainforest hardwoods may open up opportunities for other sustainably produced hardwood timber products (Beall, 2000).

Asia

Davison (2000) has suggested that “features” are not accepted in Japan where clear, clean product is preferred. However it may be possible to use shorter, “feature-docked”, clear hardwood to produce flooring. The best opportunities for products in the Japanese market are for solid timber as semi-finished flooring, solid timber for joinery, solid timber for decking and veneers for flooring and furniture production (Davison, 2000). These short clears could be produced from low rainfall grown timber, and the market opportunities may be significant as Japan is familiar and comfortable with short, clear solid timber for further processing and recombination, unlike the Australian marketplace, which is still centred around long length, solid timber production. In 1996, Australia provided 5% of Japan’s timber imports by volume (Davison, 2000).

The market for non-structural hardwoods in other parts of Asia e.g. China, Malaysia, Indonesia etc. is likely to be limited, despite anticipated strong economic growth in the region over the next decade. These economies are already geared to the production of large volumes of appearance grade products e.g. furniture from hardwoods, primarily for export. Although much of the current resource is derived from native forests, which is expected to decline, there are large areas of plantation hardwoods coming on stream in the region as a replacement resource. Given this, it needs to be recognised that in the future a more likely scenario could be that, rather than Asia being a potential market for Australian appearance products, the Australian market needs could be substantially satisfied by exports from Asia.

Europe

Nilsson (2000) predicts that Europe will have an oversupply of sawn timber by 2010, largely due to the opening up of restricted economies. As such, Europe is unlikely to develop into a large market for low rainfall appearance products, although some niche opportunities may still develop.

In summary, the best opportunities for appearance grade timbers from low rainfall areas are likely to be the domestic market, in competition with both timbers grown in predominantly higher rainfall zones and imported sawnwood, and exports to Japan. The production of plantation timbers in China and South East Asia is likely to limit opportunities in those markets, and could even impact on the opportunities in the domestic market.

Current feedstocks

In Australia, appearance timber products are currently produced from sustainably managed native forests. Appearance timbers produced from low rainfall plantations will find it difficult to compete against the native timber supply unless the costs of production, particularly drying, can be reduced significantly. However, the increased environmental pressure, both within Australia and world-wide, may reduce the harvest of native forest timbers enabling planted eucalypts in low rainfall areas to compete nationally and internationally on a world scale market.

Prospects

Minimum sawmill throughput and plantation estate

Studies undertaken by CSIRO Forestry and Forest Products (FFP) on low-rainfall species indicate that a high quality product can be produced from a low-rainfall resource (Washusen and Waugh, 2000; Blakemore *et al*, 2001). Previous studies on East Gippsland eucalypts have shown that multiple saw techniques can be successfully employed on high-density eucalypts (Northway and Waugh, 1999). Given the capital infrastructure costs for sawing, drying and further processing, it is anticipated that the minimum economically viable sawlog throughput would be approximately 30,000 m³ of green timber. Using the Wood Futures^{©1} model (Waugh *et al*, 2001) and assuming a mean annual increment (MAI) of 5 m³ / ha / yr, and a rotation of 35 years, it is predicted that a 20,000 ha estate with an annual harvest of 570 ha would be required i.e. about 5% of the land within a 35 km radius, or 1% of the land area within an 80 km radius. This assumes an initial planting at 850 stems / ha, followed by non-commercial thinning, pruning to five metres, two commercial thinnings for round timbers to a final crop of 120 stems / ha at age 35 years. The model showed that, without thinning, log sizes would be much smaller and a relatively greater volume of residue wood would be produced. It should be noted that these predictions must be viewed with some caution, as the Wood Futures[©] model was primarily developed to predict wood flows from blue gum plantations.

Likely production costs for sawn appearance grade timbers will depend on a number of factors, including: the input capacity of the mill; the capital investment and level of technical sophistication; mean log diameter; log quality; mean haulage distances for logs; ease of drying of sawn material; mean shrinkage of sawn product after drying; recovery rates for sawn product. Using the Wood Futures[©] model it has been estimated that production costs for a mill with a 30,000 m³ annual log input could be as low as AU\$500 / m³ of output product (assuming the wood raw material costs to be AU\$180 / m³ of output product). However, accurate data for sawing and drying costs in particular are not easy to derive, and estimates for these vary widely. Table 3 summarises the range of costs that could potentially apply for different parts of the operation; the information is largely based upon unpublished data supplied by Washusen (2003). It is evident that the total cost per m³ of output product is heavily influenced by the recovery rate (percentage of log sawn into dried products), which can vary from less than 30% to nearly 40%. Log quality, ease of drying and mean shrinkage are key variables determining the recovery rate. It may be seen that in the worst case, overall production costs for sawn hardwood could exceed AU\$850 / m³ of output product, inclusive of log costs.

Table 3: Estimates of costs for hardwood saw-milling process variables

Variable	Units	Value
Log cost (at stump)	\$ / m ³ (input)	35 - 80
Harvesting	\$ / m ³ (input)	20 - 25
Haulage	\$ / km / m ³ (input)	0.1 – 0.2
Sawing	\$ / m ³ (input)	80 - 120
Drying	\$ / m ³ (output)	80 - 150

¹ Wood Futures[©] model is a Microsoft ExcelTM based model which predicts wood flows (volume and size) and potential products for plantation grown timber.

It has been suggested that processing costs could be significantly reduced in mills with much larger processing capacity e.g. 25 000 m³ / annum input capacities or greater. It is assumed that such mills would be more akin to modern softwood sawmills, with high volume throughputs and lower unit processing costs. However, it is not at all clear whether such mills would be viable for processing hardwoods grown in dispersed lots in low rainfall regions, with log diameter, log form and haulage costs all likely to be critical factors.

Products

As discussed above, in order to achieve high value products it would be necessary to undertake significant silvicultural management of the stand. A number of species that have shown some growth potential in low-rainfall areas have been studied for their sawn product potential. To date un-managed trees have been used, so there is considerable potential for product recovery improvement. An indication of the potential of some selected species is shown in Figure 2. Figure 2 shows the recovery of dried, high quality appearance products that were graded 'Select' quality or better. This recovery of high-quality products is expressed as a percentage of the total sawn out-turn of target products. It is a good measure of log quality without taking into account differences of log size and sawing systems that are reflected in the overall sawn recovery rate. The grade of product which can be obtained from logs has a significant impact on the overall profitability of an operation. For example, Select and Standard grades of material can be worth between \$800 and \$2,500 / m³, whilst Utility grade material can be worth as little as \$350 / m³.

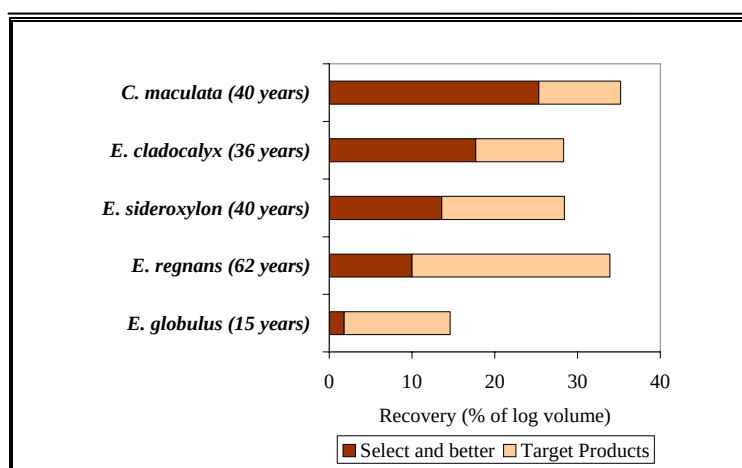


Figure 2: Recovery of high-quality, dried, back-sawn appearance products (Select Grade and better) and target products from selected medium-low rainfall plantation grown trees with comparisons with quarter-sawn recovery from native forest grown *E. regnans* (from Washusen and Waugh, 2000)

Processing costs can be minimised by targeting a narrow range of product dimensions which could be further processed for appearance products such as (modified from Waugh *et al*, 2001):

- Thin-section overlay flooring (5-12 mm final thickness), requiring high hardness and few inherent defects. Supplied in a wide range of lengths, with a premium for lengths of 2.4 metres or longer. Unit shrinkage and colour uniformity are important issues.
- Strip flooring (15-20 mm final thickness), requiring high hardness and stiffness, in addition to the attributes mentioned above.
- Furniture and furnishing stock (15-20 mm final thickness), where hardness and stiffness is less important and some inherent characteristics such as small tight knots are acceptable. There is no advantage in longer lengths. Often laminated for increased thickness and / or width.
- Thick-section furniture stock (35 mm final thickness) as short lengths with high quality requirements.

Sawing

Plantation sourced logs will have the advantage of relative uniformity in size and quality compared to those from native forests, even though they may be small, knotty and contain high growth stresses. This is the first requirement to move into higher production systems, following the lead of the softwood industry. Sawing systems and procedures will need to:

- minimise operator decision-making
- produce high sawing rates and high product recovery with accurate sizing
- progressively relieve growth stresses, preferably using multiple sawing systems to balance stress relief so products with distortion levels, which can be accommodated by handling, drying and further processing systems, are produced (Waugh, 2000).

Drying

The drying rate and quality of the product is affected by the inherent wood structure and by the thickness and sawing orientation of the boards. Green sawn material from low rainfall produced timber could span a range of thicknesses from 42 mm down to possibly 12 mm, and would be predominantly backsawn.

Drying low rainfall grown timber will be a time intensive process, particularly if thicker boards are sawn. When drying backsawn wood for appearance end-uses timber handling during the early stages of drying is critically important, and must be undertaken in high humidity and low temperature conditions to minimise surface checking. The greatest amount of drying degrade can occur in the early stages of drying and the timber should be protected from harsh environmental conditions immediately post sawing. A range of progressive and large zone controlled environment warehouse pre-dryers are being used in Australia for drying south-eastern eucalypts which are prone to internal checking and collapse. There will be a need to evaluate what system will be best suited for drying low rainfall grown eucalypts to the quality required, and the drying strategies required to achieve this. The opportunity also exists for the application of novel drying systems, such as vacuum radio-frequency drying of thicker-section, short lengths.

Most of the low rainfall species do not show pronounced cell collapse during drying. This means that steam reconditioning prior to final drying is not essential, allowing considerably more flexibility in the type and the design of drying systems. Generally appearance end-use low rainfall grown timber products should be dried to about 10% moisture content.

Further processing

The potential for further processing of low rainfall grown eucalypt timber will depend on the quality of the resource, product dimensions and market needs. Opportunities exist in a number of areas (Ozarska, 2000):

- thin section overlay flooring, backed by either sawn softwood or composite panel products
- decorative laminated table and bench tops
- short-length components for furnishings in the furniture industries
- high-strength engineering products, finger-jointed and laminated to beam and lintel dimensions, where individual components can accommodate a higher drying degrade than possible with appearance products.

Gluing and surface finishing

The selection and performance of adhesives is an essential element in using low rainfall grown eucalypts in further processed products. The ability to glue components together is essential in the production of products such as thin overlay flooring, bench-tops, furniture components, veneer, plywood and LVL products (Ozarska 2000). To date there has been limited work in testing bond strengths with various glues and resins with low rainfall grown eucalypts. In adhesive and surface finishing trials carried out by Ozarska and Ashley (1998), they found:

- PVA and urea formaldehyde adhesives typically gave unsatisfactory bonding performance and some limited success was achieved with epoxy adhesives when used with high-density species.
- No problems were found with discoloration due to the presence of extractives and the different lacquer and oil-based stains that were tested performed best on the higher-density species.

Veneer products

Veneer logs typically comprise large diameter, clear straight logs. It is unlikely that any veneer logs will be produced in the first rotation of low rainfall eucalypt plantings because of the lack of breeding improvement for large dimension, straight stemmed trees with reduced branching. It also remains to be determined whether any sufficiently large logs may be produced in the low rainfall areas, as traditionally, low rainfall grown trees remain relatively small due to water limitation.

Despite these caveats, intensive management combined with a minimum of 35 years rotation length may result in trees of 40 cm diameter or larger to produce veneer products. High densities would make rotary peeling very difficult and also difficult to achieve adequate bond strength for engineered products. However, opportunities may exist for producing thin sliced decorative veneers using equipment such as the small-scale Manataka longitudinal slicers; these are successfully used in Tasmania to process high-density East Gippsland species. This equipment would use selected sawn flitches and would produce a product which exhibited the same decorative features as sawn products.

Likely required plantation area to meet market demand

It was stated earlier that the predictions from the Wood Futures© model must be viewed with some caution. However, in the absence of any other reliable data pertaining to hardwood plantations in low rainfall regions, the model outputs are currently amongst the best available guides to likely scenarios where low rainfall hardwood plantings are concerned. Based on the likely future markets for appearance grade products, the model predictions can also be used to broadly estimate the total areas that *could* be planted with low rainfall hardwoods. For example, assuming a sawn product recovery rate of around 40% and penetration and capture of the entire Australian market for non-structural hardwood timber, an area of approximately 2 million hectares would be needed to meet this demand. This equates to approximately 2.5% of the 80 million hectares of agricultural land in the salinity zone in Australia.

In reality it is extremely unlikely that the entire Australian market for non-structural hardwood timbers would be captured by a hardwood plantation industry based in low rainfall areas. It also needs to be recognised that the sawing residues alone from an industry of such a scale could amount to around 1.5 million air dry tonnes per annum. Significant quantities of small roundwood would also be produced. To put this in perspective, assuming they were suitable, the sawing residues alone would be sufficient to facilitate the production of around 3 million m³ of medium density fibreboard (MDF) per annum i.e. about 5 times the current annual production in Australia, or almost half the current annual production in Asia.

A low rainfall hardwood plantation industry geared to the production of appearance grade products would undoubtedly face fierce competition from a range of sources, primarily its Australian higher

rainfall counterpart and similar overseas industries. This would significantly reduce the potential market size for product and the consequent plantation area required to meet the demand. Improvements in low rainfall plantation productivity would also certainly accrue, further reducing the required plantation area. Whilst a range of future scenarios could be envisaged or proposed, it is believed that a planted area equating to approximately 800,000 hectares, or 1% of the total agricultural land estimated to be in the salinity zone would likely comfortably meet all potential demand for appearance grade wood products.

Conclusions

The increased environmental pressure on native forests, both within Australia and world-wide, may reduce the availability of this resource to the saw-milling industry and the market place. This reduced availability could provide an opportunity for appearance sawn and veneer products from low rainfall plantings to enter the market and compete effectively. Studies at CSIRO FFP have shown that low-rainfall species can produce high-value products with some features and colours that cannot be obtained from species growing in higher rainfall regions. However, low rainfall grown appearance products will still have to compete with high rainfall grown plantation timber, and the relative economics and efficiencies of these competing production systems have yet to be fully elucidated. Certainly, the current MAI's that are typical with low rainfall systems would suggest that such systems could be seriously disadvantaged.

Appearance sawn and veneer products could potentially be produced economically from low rainfall grown eucalypt plantings, provided:

- genetic improvement in planting stock leads to improvements in growth rate, form and branching habit
- intensive silvicultural management can produce trees of more than 40 cm diameter, from which high quality logs can be harvested
- an adequate scale of processing can be achieved to enable the industry to realise necessary economies of scale
- optimal drying strategies and schedules are developed for low rainfall species
- further processing, including gluing, machining and stability, attributes are developed
- markets are found for sawing residues and small roundwood.

It is estimated that if low rainfall grown appearance products could gain a substantial share of the market i.e. at least 500,000 m³ / annum of sawn and dried product, then the land area required for a sustainable plantation-based industry would probably amount to no more than 1% of the 80 million ha of agricultural land in Australia's salinity zone.

Dry formed fibreboard

Introduction

When considering the 'family' of wood-based panels, medium density fibreboard (MDF) has undoubtedly been the growth product of the last twenty years (see Figure 3). MDF is a dry formed fibre-based product, typically produced in flat sheet form in a range of thicknesses (most commonly between 3 and 40mm). Panel density can range from around 650 to 900 kg / m³, thinner products normally being of higher density. The primary bond holding fibres together is obtained by the addition of synthetic thermosetting adhesives; the choice of adhesive type is dictated by the intended end use of the product. A key property of MDF is its machinability (both edge and surface), which has enabled the product to penetrate significantly into the furniture market, substituting both solid wood and other panel products e.g. particleboard, plywood etc.

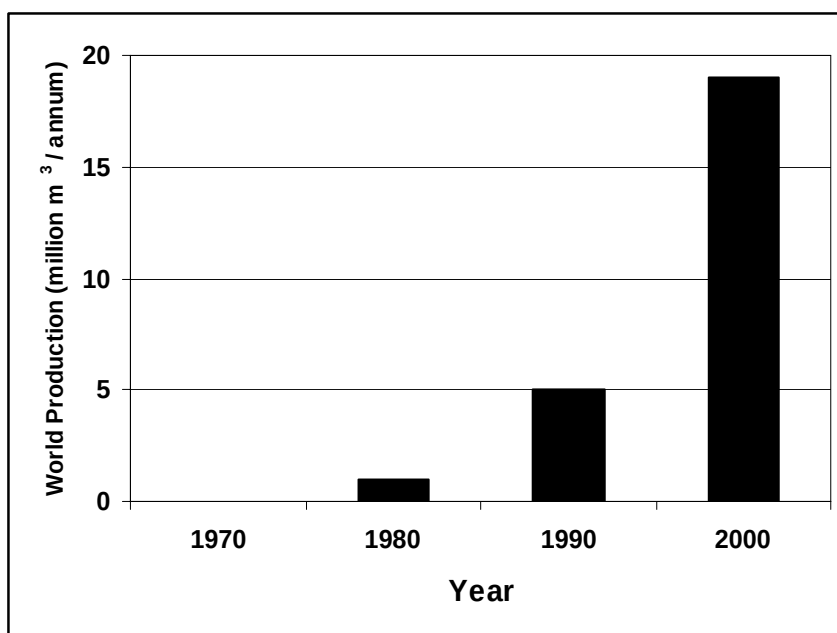


Figure 3: World production of MDF, 1970-2000

Since its invention in the late 1960's in North America, MDF has undergone significant changes both in terms of the technology used for its production and the different types of product produced. In terms of technology the biggest change has undoubtedly been the introduction of continuous hot presses. Whilst requiring high capital investment, these have introduced significant economies of scale into the manufacturing progress. They have also made possible the economic manufacture of thin (less than 6mm thickness) products.

MDF has developed and differentiated to such an extent that there are currently at least seven distinctly different types of dry formed fibreboard now recognised in the market place. These product types are primarily differentiated by their density and durability. At least three different density ranges of product are recognised: low density (LDF, or Lightboard), which typically has a density less than 650 kg / m³; MDF; high density (HDF), which typically ranges in density between 950 and 1050 kg / m³. The different density products may each be manufactured using different types of thermosetting resins. Melamine, phenol and isocyanate (MDI) based adhesives are used to produce moisture resistant (MR) grades of panel. The latter are increasingly used for the

manufacture of HDF, with the product being aimed at a variety of more demanding applications e.g. laminated flooring. HDF produced in moulded form is an increasingly common form of the product, it predominantly being produced as ‘skins’ for the interior door market. Some is also produced for use in the automotive industry. Some dry-formed fibreboard is also produced containing additives which promote resistance to spread of flame; such products are termed fire resistant (FR), and are intended primarily for use in applications such as shop fitting etc.

In this review the term MDF is used in its broadest sense to describe and encompass all types of dry-formed fibreboard that are currently manufactured around the world.

Markets

Production (capacity) and consumption

The MDF industry witnessed an explosion in investment in production capacity throughout the second half of the 1980’s and through much of the 1990’s. Much of this investment has been concentrated in Europe and Australasia. The total available world production capacity has almost doubled in the last five years (Butzelaar, 2001). This has made the MDF industry highly competitive and facilitated dramatic improvements in manufacturing efficiency and reductions in profit margins. Despite this, however, MDF is still a ‘growing’ product and has yet to enter the ‘mature’ phase of its life cycle. Indications are that world production capacity and demand for the product will continue to grow for at least another decade (Butzelaar, 2001).

Australia

The total MDF production capacity in Australia is summarised in Table 4 (Anon., 1999). The production capacity of individual production lines in Australia is relatively small compared with the latest installations around the world. Average capacities for the newest lines designed for ‘commodity’ panel production are now around 250,000 m³ / annum, with 350,000 m³ / annum not uncommon.

Table 4: Australian MDF mills and their production capacities

State	Company	Location	Production Capacity (m ³ / annum)
VIC	Dominance Industries Pty Ltd	Wangaratta	140,000
NSW	Carter Holt Harvey	Oberon	250,000
QLD	Laminex (Fletcher Wood Panels)	Toolara	250,000
WA	WESFI (Fletcher Wood Panels)	Welshpool, Perth	100,000
TAS	Carter Holt Harvey	George Town	120,000
		Total	860,000

It is evident from Table 5 that over the last few years the production capacity in Australia has not been fully utilised (ABARE, 2002). This is likely to be attributable to two factors. Firstly, it takes time to fully commission new installations and bring them up to their full design production capacity.

Secondly, the market often cannot instantly absorb all new production capacity as it comes on stream. Over time the available production capacity would be expected to be fully utilised.

Table 5: Production and consumption of MDF in Australia (m³ / annum)

	Financial Year		
	1999-2000	2000-2001	2001-2002
Production	621,000	712,000	732,000
Imports	138,000	88,000	81,000
Exports	288,000	389,000	403,000
Apparent Consumption	471,000	411,000	410,000

Asia

Accurate data for the production and consumption of MDF in Asia is difficult to come by. However, production capacity in Asia has been estimated to be around 6.5 million m³ / annum in 2000 (Butzelaar, 2001).

Europe

Production capacity has expanded rapidly in the last five years in Europe. Figures for production and trade are given in Table 6 (Anon., 2000a). It is evident that whilst significant trade in MDF occurs between Europe and other regions, consumption of MDF in Europe closely matches production.

Table 6: European production and trade of MDF (×1,000 m³)

	1996	1997	1998	1999
Production	4,348	5,514	6,619	7,299
Export	1,840	2,540	2,794	2,928
Import	1,555	2,277	2,621	2,764
Apparent Consumption	4,063	5,251	6,446	7,135

North America

Production and trade data for North America over recent years are shown in Table 7 (Anon., 1999). It may be seen that growth, whilst significant, has not matched that seen in Europe.

Table 7: North American production and trade of MDF ($\times 1,000 \text{ m}^3$)

	1996	1997	1998	1999
Production	2,272	2,691	3,192	3,394
Export	271	446	723	963
Import	318	468	704	973

End-uses for MDF

MDF is not a truly structural product, the relatively high creep coefficient of the product in particular precluding its use in long term load bearing applications. Whilst an increasing proportion of HDF is being used for flooring applications, especially laminated flooring, the predominant use for MDF is still in furniture, millwork, mouldings and shop fitting.

The MDF manufacturing process

Raw materials used for MDF manufacture

Wood is used almost exclusively for the manufacture of MDF world-wide. Furthermore, softwood is more often than not the preferred choice. This is because softwoods:

- are of lower density
- contain longer fibres (and therefore generate less dust, lowering resin usage and fire risk)
- contain lower levels of extractives (thus maximising fibre yield and minimising effluent)
- have more ‘user-friendly’ chemical properties e.g. pH.

MDF is currently predominantly manufactured from softwood in carefully prepared chip form, although ironically a key driver for the development of MDF in North America was originally the need to utilise lower grade sawmill residues (sawdust etc.) which couldn’t easily be utilised in other products (pulp, particleboard etc.). Where softwoods are scarce, MDF is made from hardwoods e.g. Eucalypts in South America and Spain, and Eucalypts, Acacia and rubber-wood (redundant stem material from spent latex plantations) in parts of Asia. Until recently attempts to process Eucalyptus for MDF in Australia had not been very successful. It is believed that this was related to the type and source of wood which was processed. Faster grown plantation material is likely to be much better suited to the manufacturing process.

In recent years there has been increasing interest in utilising alternative raw materials for MDF manufacture. This interest has largely been cost driven. Residues from agriculture (e.g. cereal straws), dedicated fibre crops (e.g. flax, hemp, miscanthus grass, short rotation *Salix* and *Populus* sp.) and recycled wood have all been investigated. Research results have suggested that most alternative raw materials could be utilised for MDF, either alone or in mixtures with existing raw materials (Hague *et al*, 1998).

Adhesives are required to bind the fibres together to form the finished panel. The amount of adhesive added is dependent upon a range of factors, including product type, resin type and target end use.

Typically addition rates vary between 5 and 15% (resin solids on oven dry mass of wood). The key adhesives used are summarised in the following.

Urea formaldehyde (UF)

The ‘work-horse’ of the MDF industry. It is used extensively to produce standard type products destined for general indoor use. The resin is relatively cheap, is fast curing and possesses good tack properties. The drawback is that the resin does not perform well in high humidity / exterior conditions. This is in part because it is susceptible to hydrolysis, and also because it is relatively crystalline and rigid; this latter property can result in the catastrophic failure of bonds as wood particles and fibres swell within the product. In recent years the F:U ratio of UF resins has been significantly reduced. This has resulted in lower formaldehyde emissions (both during manufacture and from the finished product) and has largely addressed many of the major concerns regarding exposure to formaldehyde. However, the changes in resin formulation have also reduced their reactivity and efficacy; consequently, resin dosing rates have crept up in recent years.

Melamine urea formaldehyde (MUF)

Where improved product moisture resistance and dimensional stability are required, MUF resins are frequently used. The proportion of melamine used is dictated by product performance requirements and cost (melamine is considerably more expensive than urea). The mechanisms involved in the blending of urea, melamine and formaldehyde and their subsequent interaction are not fully understood; there is potential for improvement in the formulation of such resins. MUF resins are used where speed of cure i.e. productivity is still an over-riding consideration; products are not typically suitable for use in environments of repeated exposure to high humidity or true exterior conditions.

Phenol formaldehyde (PF)

PF adhesives are used to produce moisture resistant products. Compared with UF / MUF adhesives, PFs are more durable and flexible. Accordingly, products have superior performance, and where failure does occur it tends to be in the wood rather than the adhesive. One of the traditional drawbacks to using PF adhesives has been their relatively slow rates of cure and lower moisture tolerance during processing. However, in recent years progress has been made on these issues (particularly by CSIRO scientists), and undoubtedly much more can be achieved. It is worth noting that tannins can be used as whole or part replacements for phenol, and indeed are in some instances. The drawback to using them is that they are a naturally derived material, and the inevitable variability this brings can create quality control problems in the mills.

Methylene diphenylene diisocyanate (MDI)

MDI adhesive has been in existence for a number of years. Despite the fact that it is an extremely effective adhesive which can impart true ‘exterior’ properties to products, its adoption by the industry has been slow. This is due to a number of factors:

- MDI is relatively expensive
- MDI is such an effective binder that it has the capacity to (and has!) block blowlines and dryers, and stick press platens together. This introduces additional processing / maintenance costs.
- Prolonged exposure to non-cured MDI can potentially result in sensitisation in mill workers
- MDI lacks natural tack – this can cause problems where maintenance of mattress integrity prior to pressing is important.

Because of the above issues and problems, MDI tends to be used primarily to produce specialised (exterior, ‘zero’ formaldehyde etc.) MDF products, where the additional production costs can be amply offset by the added value.

Other additives

The other principle additive included in MDF is wax. This is included in order to impart short term resistance to thickness swelling. Wax may be added either in molten form or as an emulsion, depending on mill location, product type etc.; to date there is little hard evidence that either wax type offers advantages over the other in terms of finished product properties. Addition rates are commonly less than 1% wax solids on oven dry wood mass.

A whole range of other additives can potentially be added during the manufacturing process, including adhesive catalysts, formaldehyde ‘catchers’, biocides and fire retardants.

Overview of the MDF manufacturing process

A schematic overview of a typical MDF manufacturing plant is given in Figure 4.

Debarking and chipping

MDF manufacturers generally prefer to use bark-free wood. This is because included bark particles can reduce panel surface quality. Accordingly, roundwood is debarked prior to chipping. Most modern mills use drum de-barkers to achieve this step, the bark being removed by the action of logs tumbling and rubbing against each other and the internal surface of the drum. Debarked logs are then reduced to chips using disc chippers. Likewise, sawmills will debark saw logs prior to the processing and forwarding of residues to MDF mills.

Chip screening and washing

Chips are first screened to remove fines and oversized material. Fines are commonly removed, since these can ‘blind’ the refiner / defibrator plates, and their inclusion will also reduce overall mean furnish fibre length. Oversized material is removed because it can cause power surges during refining. Screened chips are then washed to remove grit etc. This step is important, since included grit can increase wear in downstream processing equipment, in particular the refiner, and increase the tool wear of product end-users. Permissible limits for included grit in the product are specified in standards.

Fibre preparation

Fibre is produced via a process known as thermo mechanical pulping. The washed chips are first pre-steamed at around 100°C to soften them. They are then fed continuously via a plug feeder into a digester, where they are heated to around 170°C for approx. 3–5 minutes. This heating phase is important, since it takes the lignin component (which constitutes the bulk of the middle lamella between fibres) of the wood chips above its glass transition temperature (the polymer becoming more plastic-like in nature and susceptible to flow). During subsequent refining of the softened chips between opposing grooved discs, the fibres are liberated via preferential separation at the middle lamellae. This results in fibres which are largely undamaged (compared with mechanical paper pulps), with lignin rich surfaces which have good compatibility with thermosetting adhesives. The specific energy requirements of refining are also significantly reduced, typically by a factor of five.

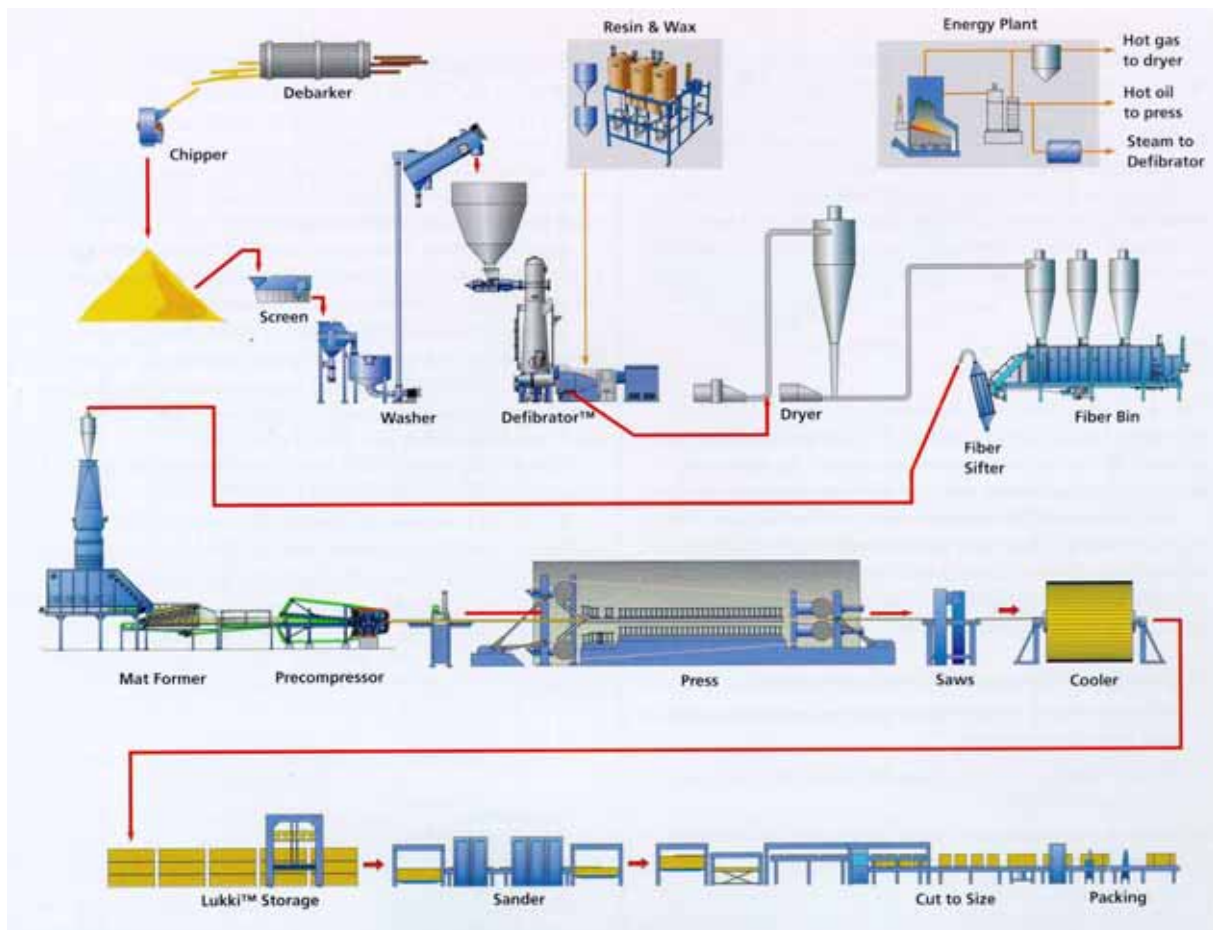


Figure 4: Schematic overview of the Metso Panelboard MDF manufacturing process

Adhesive blending

When the MDF process was first developed, refined fibre was first dried and then blended with adhesive. The blenders were typically large rotating drums in which fibre was tumbled, onto which atomised adhesive was sprayed. Whilst panels with acceptable mechanical properties were subsequently produced, there were a number of problems with the process. The most important issue was adhesive spotting on the panel surfaces due to uneven adhesive distribution. This was undesirable both from an appearance point of view and where surface finishes were applied, since the absorptive properties of the panel surfaces were variable. The blending equipment also required frequent maintenance and cleaning. Furthermore, post blending of the dried fibre with adhesive requires the fibre to be dried to low moisture contents e.g. 3%; this carries a significantly increased fire risk.

The problem of adhesive spotting was resolved by the development of the blowline blending process. The blowline is a simple tube connecting the refiner housing to the fibre dryer, down which refined fibre (and steam) is discharged. The velocities in the blowline are of the order of 100 m / s, and the flow has been shown to be fully turbulent. These conditions are ideal for atomising injected liquids and mixing them with fibre passing down the tube. Thus, blowline blending consists simply of injecting adhesive into the blowline, typically at a point within a few metres of the outlet (blow valve) from the refiner; the adhesive and fibre are then intimately blended prior to discharge into the dryer. Wax may be similarly blended with fibre in the blowline, though some manufacturers prefer to inject wax into the refiner.

A major disadvantage of blowline blending is that the adhesive must, for a short time, pass through the blowline and dryer, exposed to temperatures well above its cure temperature. This inevitably leads to some pre-cure and loss of adhesive efficiency. As a consequence, higher resin loadings are required in blowline blending compared with mechanical blending. Until recently this has been regarded as an acceptable penalty to pay in return for products free of adhesive spotting. However, the more recent changes in UF adhesive formulation, designed to address the concerns over formaldehyde emissions, have resulted in increasing quantities of adhesive being required in order to achieve acceptable product properties. This has led to renewed interest in mechanical blending options, and new technology is starting to emerge. It remains to be seen to what extent the industry might switch back to mechanical blending.

Drying

Blended fibre and steam are discharged from the blowline directly into a flash dryer. This is a tube of approximately 100m length and 2m diameter, through which heated air is blown at a velocity of around 30m / s. Inlet temperatures vary according to ambient surrounding conditions, but are typically in the range 150 – 200°C. The dried fibre is discharged into a cyclone, where the moist air and dry fibre are separated. Target moisture content (dry weight basis) after drying is around 10%.

Mattress forming

Mattresses are formed in a single layer. A variety of designs of former are used, most initially forming the mattress to a height in excess of actual requirements and subsequently using a ‘scalping’ roller to adjust the final mat height. New designs are now becoming available (e.g. Valmet ‘Uniformer’) which form the mattress in a single pass without the need to scalp.

Pre-pressing

Mats are pre-pressed prior to hot pressing, typically by passing them through belt presses. The pre-pressing process is important, as it consolidates the mattress enabling it to be more easily transported (i.e. to the hot press). Pre-pressing also reduces the height of the mattress, which facilitates faster closing to target thickness in the hot press; this is important from the point of view of minimising surface pre-cure and achieving the target density profile through the panel thickness.

Hot pressing

The hot pressing stage is important in that it has a large influence on the final product properties. The purpose of hot pressing is to:

- bring particles and fibres together in close proximity in order that adequate bonds can be formed
- raise the temperature of the mattress sufficiently throughout its thickness in order to effect cure of the adhesive and to help soften and relieve stresses developed in densified and deformed fibres
- achieve target panel thickness and density
- achieve the desired density profile through the panel thickness.

Key hot pressing variables are platen closing speed, platen temperature, mattress moisture content and pressing time. These will be tailored according to product property requirements. The processes occurring during hot pressing are complex, with considerable interaction between pressing variables. Mattress moisture content is extremely important as it dictates the rate of heat transfer from the surface to the core of the product and hence the level of steam generated within the product (and hence when the press can be opened). Typical platen temperatures are around 200°C. Mat moisture content is around 10% (dry weight basis); although this may vary between plants, in a given mill every effort is made to ensure minimal variation in mattress moisture content. Total pressing times can vary, but may be as little as 6 seconds per mm of final board thickness.

A range of press types is used for hot pressing panels. These include:

- *Multi-daylight presses.* These may typically have the capacity to press between 12 and 24 mats at a time, typically measuring 7 x 2.5m in area.
- *Single opening presses.* Only a single mattress is pressed, though it may measure up to 50m in length and 3m in width.
- *Continuous presses.* These are comprised of two heated steel belts, between which the mattress is fed on a continuous basis. The length of the press varies, being between 25 and 40m, with faster throughputs being achieved with the longer presses. Continuous presses can give significant improvements in productivity, and a whole range of panel thicknesses can be efficiently produced.

Almost all new MDF mills are now fitted with continuous presses, and many older mills have and will be retro-fitted with them. Despite their much higher capital cost and higher running and maintenance costs, it is now generally recognised and accepted that these disadvantages are more than compensated for by the improved productivity and flexibility of continuous presses.

Cooling / stacking

UF / MUF bonded boards tend to be cooled on star coolers after pressing. This is because the cured adhesives can be degraded by longer-term exposure to elevated temperature. However, even after cooling the temperature at the centre of a stack of boards may be of the order of 60°C. In contrast, PF-bonded panels may be hot stacked immediately after pressing in order to promote further cure of the adhesive and improvement of panel properties.

Sanding

Sanding of panels is performed for the following reasons:

- Removal of the pre-cured layer on the outer surfaces of panels. Pre-cure occurs because the hot pressed mattress cannot be brought to final thickness instantaneously; during the consolidation phase the outer mattress surfaces dry out and the adhesive is cured. This results in soft, loose layers on the panel surfaces which are poor substrates on which to apply finishes, laminates etc. The depth of pre-cure typically varies between 0.25 and 0.75mm on each surface; pre-cure tends to be minimised in continuous pressing operations. After sanding with appropriate grit sizes, panels have smooth high density surfaces ideal for finishing purposes.
- The variation in thickness across panels immediately after pressing is typically greater than the stipulated maximum in standards.

Modern sanding machines are multi-headed and can operate at speeds in excess of 3000m / hour. The sander dust is typically used as a fuel within the plant to generate heat energy etc.

Trimming and cut to size

Panels are trimmed and cut to size according to customer requirements. In modern mills the equipment used is large, complex and computer controlled. A number of panels can be processed at once, and the computer chooses the optimum cutting patterns based on customer orders and the need to minimise waste; sawdust and any other waste is treated in a similar fashion to sander dust. After trimming panels may either be packed and wrapped for shipment, or directed to other on site finishing lines e.g. painting, laminating etc.

MDF production costs

Reliable data for the costs of MDF production in Australia are hard to come by. Zorzetto and Chudleigh (1999) cited average 'prices' in 1997 for MDF produced in Australia of around AU\$452 / m³. However, this gives only broad indications of the likely costs of production. In addition, the industry has developed considerably in recent years, and the cost structures will have altered accordingly.

Table 8: Comparison of the production costs of MDF in various regions of the world (adapted from Wilson, 1999)

	Unit	Canada East	Brazil	Chile	Indonesia	Malaysia	Germany	Poland
Production								
Mill output	m ³ / yr	250,000	255,000	135,000	80,000	85,000	250,000	250,000
Variable Costs								
Wood	AU\$ / m ³	52.4	51.9	51.2	25.5	38.8	84.5	73.3
Electricity	AU\$ / m ³	18.9	32.3	37.1	20.1	38.1	45.4	29.1
Heat Energy	AU\$ / m ³	9.9	4.8	4.8	4.4	4.4	8.7	8.0
Chemicals	AU\$ / m ³	43.0	65.1	57.0	50.2	50.2	43.0	43.0
Operating Materials	AU\$ / m ³	8.7	6.8	7.5	7.1	7.5	9.2	6.6
Other Variables	AU\$ / m ³	4.3	3.4	3.6	3.4	3.6	4.6	3.2
Total Variable Costs	AU\$ / m ³	137.0	164.2	161.0	110.7	142.5	195.3	163.2
Fixed Costs								
Operating Personnel	AU\$ / m ³	10.5	4.4	5.3	0.7	3.4	12.2	2.9
Maintenance Personnel	AU\$ / m ³	8.7	3.7	4.3	0.5	2.2	9.7	2.0
Admin. Personnel	AU\$ / m ³	9.9	7.0	7.8	0.7	2.7	9.0	2.7
General Overheads	AU\$ / m ³	4.9	3.2	3.1	2.4	2.6	6.3	3.6
Maintenance Materials	AU\$ / m ³	17.3	17.7	23.6	29.8	28.1	17.5	16.7
Other Fixed Costs	AU\$ / m ³	2.9	1.9	1.7	1.4	1.5	3.7	2.0
Total Fixed Costs	AU\$ / m ³	54.2	37.9	45.7	35.4	40.5	58.5	29.9
Total Manufacturing Costs	AU\$ / m ³	191.3	202.1	206.7	146.0	182.9	253.8	193.1
Distribution Costs	AU\$ / m ³	82.1	92.7	104.9	111.0	111.0	22.8	33.5
Capital Costs	AU\$ / m ³	60.2	61.5	80.1	98.9	94.0	61.9	59.0
Total Costs	AU\$ / m ³	333.5	356.3	391.7	356.0	387.9	338.5	285.6

In a report commissioned by the European Commission and the Confederation of Wood Industries on the Competitiveness of the European Woodworking Industries, Wilson (1999) compared the production costs of a typical MDF plant in Europe (Germany) with that of potential competitors around the world. Whilst Australia was not included in the analysis, the data presented by Wilson are probably amongst the more detailed and reliable for current 'average' world MDF production

costs. The data are presented in Table 8. The analysis assumed that the target market for all panels was a European city on the west coast of the continent. When distribution costs are excluded, it is evident that production costs were estimated to vary between AU\$250 and AU\$310 / m³ (Wilson presented his original cost data in Euro; an exchange rate of 1 Euro = AU\$1.7 was assumed in this work). Differences were attributable to differences in personnel, raw material, energy and maintenance costs. Wood raw material costs typically constituted between 20 and 30% of the total production costs. It is estimated that production costs for MDF in Australia are of the order of AU\$270 / m³. In Australia, any new plant would probably need to have a minimum production capacity of approximately 150,000 m³ / annum of finished product in order to be economically viable. However, plants with production capacities of around 100,000 m³ / annum could be viable where production was focused on specialised / niche products e.g. thin panels.

Prospects

It is anticipated that world-wide demand for MDF will continue to grow for at least another decade. In the Asia-Pacific region demand is expected to increase at the rate of around 10% per annum to the year 2008 (ABARE, 2000). Both the current and future predicted consumption of MDF in the Asia-Pacific region represents a potential market for Australian produced MDF.

An MDF mill with an output capacity in the region of 150,00 m³ / annum requires around 100,000 tonnes (OD) / annum of wood feed-stock. It is estimated (Blakemore *et al*, 2001; Bartle, 2001) that it may be feasible to generate around 3 tonnes (OD) / annum / ha of wood feed-stock in at least some low rainfall regions. Depending on the extent of re-vegetation, this would suggest that the maximum transportation distances required to supply a typical MDF mill with woody feed-stock could be as little as 10km, and potentially no greater than around 25km. These distances are comparable to current industry norms. Furthermore, Bartle (2001) has suggested that it may be feasible to markedly reduce the total delivered wood costs at the mill gate by adopting short crop rotations i.e. three years, coupled with radical new harvesting and handling technology; this would suggest that a low rainfall zone MDF industry could at least be feasible. Bartle's estimates for productivity and raw material costs in this zone are supported by those of Enecon Pty Ltd (2001), which estimated that delivered costs for chipped mallee eucalypt material at the mill gate could be between \$28 and \$40 / green tonne. This translates to a delivered cost of between \$140 and \$200 / OD tonne of wood chip, assuming a wood content of 40% and a moisture content of 50% (wet weight basis) for the chipped mallee eucalypt material, and that the remaining 60% biomass (leaves, twigs, bark etc.) has little or no monetary value. The lower cost figure for delivered low rainfall zone wood is estimated to be in the upper cost range for delivered wood chip grown in high rainfall regions. A commercial use for some or all of the remaining biomass could lower the cost of low rainfall wood chip to an MDF manufacturer, and is likely to be imperative if investment in processing is to be attracted into this product area.

If the Asia-Pacific market does grow at the predicted rates, and a low rainfall zone MDF industry was shown to be competitive, the areas required to be planted to supply woody feed-stock could potentially exceed 3 million ha i.e. 3.5% of 80 million hectares of agricultural land in Australia's salinity zone. However, such a scenario assumes capture of virtually the whole market. This is highly unlikely, primarily because of the stiff competition that Australian producers will face from other producers in the region. For example, the wood supply is set to increase significantly in New Zealand over the next decade (the so called 'wall of wood') and MDF producers there will thus be well placed to meet expanding demand with a plentiful supply of near optimum wood raw material (radiata pine) at very competitive costs of supply. Increasing quantities of hardwood plantation feed-stocks will also become available throughout South East Asia over the next decade; reference to Table 8 clearly shows that in this region wood is already available at very competitive prices. In addition, there is also the prospect of the industry using recycled wood. This is common practice in Europe for particleboard production and, indeed, a recent MDF venture in North America has been established to utilise extensive quantities of recycled wood.

The future MDF market is thus likely to be highly competitive. Given this, a more realistic goal for any low rainfall zone MDF industry is probably around 10% market penetration in the longer term in the Asia-Pacific region. Such an industry would require in the region of 500,000 ha of plantation area in order to sustain it, i.e. 0.6% of the agricultural land in Australia's salinity zone. The woody feed-stock would also obviously have to have acceptable properties to ensure that resulting products met specified requirements.

Conclusions

MDF is still in the growth phase of its life cycle. Predicted increases in demand for the product in the Asia-Pacific region alone over the next decade equate to the annual output of between 3 and 7 new mills in successive years. This, combined with the existing regional industry, represents a significant potential export opportunity for the Australian MDF industry. Whether this can be met in part or wholly by the supply of woody biomass from low rainfall areas depends on a number of factors:

- competition from raw materials grown in high rainfall areas
- competition from MDF producers outside of Australia
- competition from other fibre sources e.g. recycled wood, agri-residues
- the development of radical new approaches in low rainfall areas to generating woody biomass with the appropriate properties.

Wood-plastic composites

Introduction

As their name suggests, wood-plastic composites (WPCs) are materials which are comprised of a mixture of wood and (thermo) plastics. They are defined as being materials which are comprised of at least 50% wood; where the wood content is less than 50% the materials are more correctly defined as plastic lumber (Smith *et al*, 1999). For many years WPCs were manufactured primarily for the automotive industry, being used in the form of non-structural, moulded interior components. However, in the last decade North America has witnessed an explosion in the production of WPCs, with a wide variety of products now being produced to service a much broader market (Smith *et al*, 1999). The lower grades of material are used for a wide variety of outdoor uses where strength and stiffness are not critical e.g. outdoor furniture, landscape timbers, bins etc. Higher grades of material are used for applications such as decking, doors, windows, siding and marine structures such as pilings and piers.

WPCs have penetrated markets which have traditionally been serviced by plastics or, in particular, wood alone. A key driver for the substitution of wood has been the concern over the potential health and environmental impacts of preservative treated wood. The recent legislative moves in the USA towards the banning of CCA treated timbers in domestic applications is a prominent example of the level of such concern. Other advantages that WPCs offer over wood include improved dimensional stability, increased resistance to biodegradation and low / zero maintenance requirements (Smith *et al*, 1999; Wolcott and Englund, 1999).

The strong growth in the production and utilisation of WPCs witnessed of late in North America is expected to continue for the foreseeable future. However, in Australia the industry is in its infancy, with people only just beginning to become aware of the possibilities that WPCs offer. It is believed that the relatively small scale of the manufacturing facilities, the wide variety of wood raw materials that could be used in products and the ability to add significant value make WPCs a potentially attractive option as regional enterprises in low rainfall areas.

Markets

The principal market for WPCs is currently in North America. WPCs have been extensively researched in the USA, and the commercial market is now expanding rapidly. Sales of WPCs trebled in the period 1990 to 2000, with sales exceeding 300,000 tonnes in 2000. The total market size is expected to more than double by 2005, with annual projected increases in production of 60% for the next 5 years for some products (Wolcott, 2001). WPC deck-board production has doubled annually since 1996, and in 2000 alone ten new production start-ups were initiated.

The range of WPC materials used in the North American building products industry is now quite extensive, and includes such products as vinyl siding, window and door framing. Along with decking boards, the products are designed for long-term durability and low maintenance. The materials have made large in-roads into market areas where traditional wood products have not performed well. The products also compete with aluminium for market share. Decking applications including deck boards, railings, stairs, docks and boardwalks represent over 60% of the market demand. However, WPCs still only account for a small part of the more than 11.8 million m³ of all materials used in the USA for decks and railings. There is considerable potential to make inroads into both this market and others.

A small amount of wood-filled vinyl weather-boards is currently imported into Australia. Currently there is only one commercial manufacturer of WPCs in Australia (principally decking). A number of

other interested parties are known to be assessing the merits of the products, and it is highly likely that additional start-ups will occur over the coming years.

The potential market size in Australia for WPC products is estimated to have a current value of around AU\$5 billion per annum. This represents the total market for windows, doors, facias, architrave, decking etc. Even modest penetration of this market would facilitate the creation of a significant new industry in Australia. The export market for WPCs could also be considerable. The products could be highly suitable for a number of applications throughout South East Asia, where resistance to moisture and biodegradation are highly desirable material properties.

Overview of the production process

The wood plastic composites production process is relatively simple. Typically wood is milled or refined to the required particle dimensions and mixed with pelletised plastic. The product is produced using conventional plastics processing equipment e.g. extruders or injection moulders. Important process variables include moisture content and wood extractives content. Excessive moisture or low temperature volatile extractives can result in unacceptable poor surface finishes to some products. However, recent advances in processing technology appear to be capable of overcoming these problems.

Raw materials

Traditionally wood has been used in the form of a particulate or 'flour' when mixed with thermoplastics. In this form the wood is used primarily as an extender or lower cost filler in order to reduce the costs of virgin plastics. However, where reasonable adhesion can be effected at the interface between the two phases, the wood particulate can act as a reinforcement. In recent years much research effort has been directed towards improving the performance (strength and stiffness) of WPCs by using wood fibres as a true reinforcement. The majority of research has been targeted at improving the interfacial bonding between wood and plastic due to the large differences in surface characteristics of both materials i.e. a naturally low miscibility. Technologies now exist for processing wood-plastic composites which utilise compounding aids and coupling agents to produce products with improved mechanical performance.

A wide range of wood species are apparently used in North America for WPCs, with pine (*Pinus* sp.), maple (*Acer* sp.) and oak (*Quercus* sp.) being amongst the most important. Wolcott and Englund (1999) have suggested that the choice of wood species is dictated more by availability rather than a conscious choice based on knowledge of properties imparted by a given species. However, Englund and Rutherford (1999) have suggested that whilst WPCs can be made from a variety of wood 'waste' materials, wood species is an important variable which can have a significant influence on product properties. This is clearly a topic that warrants further investigation.

The plastics used in the manufacture of WPCs belong to the thermoplastic class of polymers. These differ from the thermosetting polymers in that thermoplastics can be repeatedly softened and melted with increasing temperature. There are a wide range of thermoplastic polymers which are potentially available. However, for WPCs the choice is normally restricted to those which can be softened or melted at or below 210°C. This is because wood is seriously and rapidly degraded at temperatures above 210°C (Wolcott and Englund, 1999). Common polymers which fit this selection criterion are the polyolefins, which include polypropylene (PP), low density and high density polyethylene (LDPE and HDPE), polyvinyl chloride (PVC) and polystyrene (PS). Polyethylene is probably the most widely used plastic, and it is estimated that up to 75% of waste plastics are comprised of polyethylene.

Plastics can be used in a variety of forms, such as pellets, powder, films or flakes. Either virgin or recycled plastics can be used, though virgin plastics are often preferred where final product quality is important. The ability to use recycled plastics is an attractive option because of cost and environmental benefits, but quality control can be an issue. This is being addressed to some extent through improvements in waste sorting technology.

Product manufacture

One of the keys to successful WPC product manufacture is intimate mixing of the wood and polymer. The aim is to optimise the process such that the desired level of mixing is achieved without causing excessive damage to the wood component. A variety of equipment types are available to effect the mixing and production of components, with various types of extruder and injection moulders being the most common. These have the capability to melt the plastic component, mix components, pump and convey the mixtures and form the finished product in one continuous operation if desired.

Extruders can be of either single or twin screw design. The screws in the latter may or may not intermesh, and can either be counter or co-rotating. The choice of set-up is dictated by the properties of the raw material, the degree of mixing required and the type of product being produced. A good overview of the relationship between equipment design and other processing variables is given by Wolcott and Englund (1999). Some of the latest production systems involve tandem arrangements of extruders, with a single screw side injection extruder mounted at right angles to the main or primary twin screw extruder. The wood raw material is fed into the first section of the primary extruder, where it is heated and any moisture vapour or other volatile substances are removed by a vacuum venting system. The plastic component is heated, melted and mixed in the single screw side injection extruder, the melted plastic being injected approximately midway along the barrel of the twin screw extruder. This set-up facilitates very good mixing of the components and minimises problems such as out-gassing and vapour encapsulation.

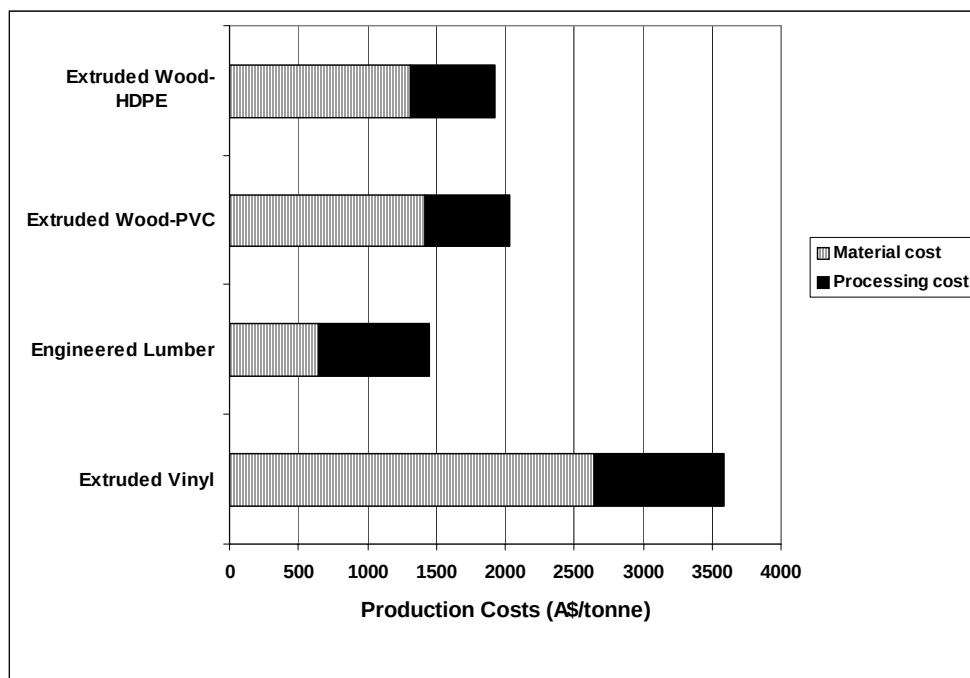


Figure 5: Materials and processing costs for extruded plastic, wood-plastic and engineered lumber (from Wolcott, 2001)

The production costs for selected WPCs are compared with those for a typical engineered lumber product in Figure 5 (Wolcott, 2001). Whilst the processing costs are similar in all cases, it is evident that the higher cost of virgin plastics is the key factor in making wood plastic composites more expensive to produce. However, it should be noted that the figures for WPC production costs given in Figure 5 represent the likely upper limits for costs, and that altering process variables will in turn change and reduce costs. In this respect important variables include the ratio of wood to plastic used in the composite, the form in which the wood is used e.g. flour, flake or chip etc., and the type of plastic e.g. virgin or recycled.

In the case of an HDPE WPC, it is estimated that raw material costs could vary between \$400 and \$1,500 per tonne of product and that the overall production costs could in turn vary between \$1000 and \$2,100 per tonne of product. These figures are based on a fixed 'processing' cost (i.e. not including the costs of wood milling etc.) of \$600 / tonne of product, clean, recycled HDPE costing approximately half that of virgin HDPE (\$2000 / tonne), milled wood costs varying between \$50 / OD tonne (non-graded, coarse chip) and \$500 / OD tonne (finely milled and graded flour) and the wood content of WPCs typically varying between 50 and 65% by mass. Assuming wood milling was performed as part of the total processing operation, and that base wood costs varied between \$50 and \$100 / OD tonne, production costs less the cost of the wood raw material could thus vary anywhere between \$900 and \$2,050 per tonne of product.

Extrusion of wood-plastic composites offers continuous production, any length of section required, an assortment of profiles and the ability to produce hollow-core boards (saving significantly on raw material costs) (see Figure 6). Simple heated platen pressing may also be used to fabricate sheets and panels. A typical individual extruder or extrusion system might have an output capacity of between 500kg and 1 tonne / hour of product. Accordingly, a small production facility might only require as little as 500 tonnes of dry woody biomass per annum.

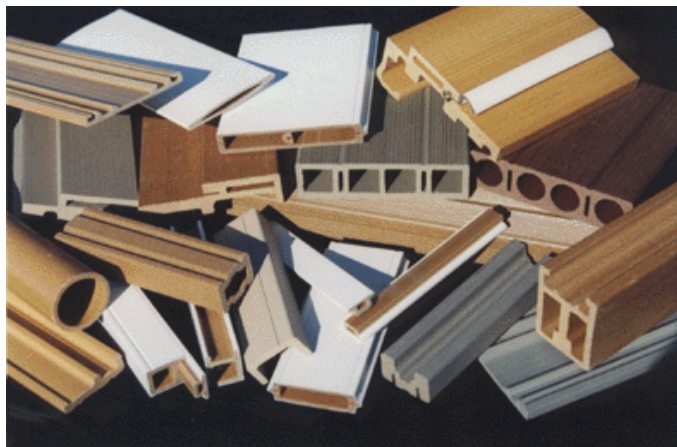


Figure 6: Examples of extruded wood-plastic composite profiles

In North America a number of corporations have operations of much larger scale. The main companies are Advanced Environmental Recycling Technologies Inc., Crane Plastics, Louisiana-Pacific Corporation, CertainTeed Corporation, U.S. Plastic Lumber Corporation and Trex Company Inc. More recently Boise Cascade has begun construction of a new dedicated plant for wood plastic composites production in Elma, Washington state, costing approximately US\$70 million. The siding plant is expected to use 74,000 tonnes of wood waste and around 45,000 tonnes of plastic waste per annum (Loney, 2001).

Prospects

There is currently some uncertainty as to how well WPCs would perform in the longer term in the Australian climate. Plastics are heat and UV light sensitive, and these issues will probably require investigation. Assuming no serious product performance issues are identified, prospects for establishing a viable Australian WPC industry would appear to be good. Australia has a mature plastics industry, familiar with extrusion and injection moulding technologies. The capital costs of production plants is also not prohibitive, and small stand alone production units in rural areas is therefore a potentially viable option. What the ultimate market size in Australia might be is difficult to estimate with any precision. However, 50,000 tonnes per annum of product in 2010 with a value of AU\$200 million is believed to be a reasonable estimate. Whilst this would be a significant industry in terms of its value, it should be noted that the planted land area required to generate the wood feedstock would be negligible in the context of the total area of agricultural land in the salinity zone.

There are potentially excellent synergies between a future WPC industry and an appearance grade products industry based in low rainfall areas. The latter would generate considerable quantities of residues, at least a proportion of which could be suitable feed-stocks for WPCs. Such a market for the residues could be important for determining the viability of a sawn-wood industry. This, however, requires further investigation. Similarly, the extent of the suitability of the residues could well be a crucial factor in determining whether a low rainfall WPC industry could compete with ones based in urban locations. The latter would likely have a number of cost advantages e.g. access to low cost wood residues from wood processing industries (furniture), low cost recycled wood and plastics and shorter distance to markets.

Conclusions

Wood plastic composite materials represent a potentially viable option for utilising woody biomass grown in low rainfall areas. In terms of value, potentially sizeable domestic and export markets exist for the products. In terms of rural development in Australia, the potential synergies with the sawn-wood industry offered by a WPC industry and the relatively modest capital investment required are appealing. However, there are still some uncertainties that would need to be resolved before significant investments were made in a low rainfall based industry. There is little or no current production of WPCs in Australia, and the performance of the products in the Australian and other sub-tropical environments will need to be fully evaluated before potential market sizes can be accurately estimated. The suitability of woody residues from low rainfall regions for WPCs is also unclear, and needs to be evaluated more fully. Furthermore, it is not clear how competitive such an enterprise would be when compared with an urban-based industry with ready access to low cost recycled raw materials and markets for its products.

Electricity from woody biomass

Introduction

The generation of electricity world-wide is largely achieved through the burning of fossil fuels (coal, gas, oil etc.). Because of the considerable demands for electricity, its generation thus represents a highly significant contribution to the total greenhouse gas emissions from all human activities. It is estimated that around 57% of Australia's total energy sector carbon dioxide emissions are attributable to stationary sources, predominantly from power generation (Fung *et al*, 2000). It is not surprising therefore that there is considerable interest in alternative CO₂ neutral (i.e. renewable energy) approaches to producing electricity. Wind, water, solar and the combustion of biomass represent some of the more obvious potential sources of renewable energy.

The generation of energy from biomass sources such as wood (often termed "bioenergy") has been around since the discovery of fire! Other forms of biomass, such as sugar cane bagasse, are also used extensively as energy sources. Thus, in Australia, sugar mills, many sawmills and most major wood processing plants already use some, or all, of their lignocellulosic wastes for the generation of heat, steam or power. Whilst some sugar mills export power into the grid, at present there are no known wood-fired power plants in Australia that do likewise.

The Federal Government of Australia has introduced a target (the Mandatory Renewable Energy Target (MRET)) for new electricity generation from renewable resources amounting to an additional 2% of total electricity production. It is envisaged that the capacity will be progressively installed up to the year 2010, and will amount to 9,500 GWh / annum of additional electricity generation capacity. This corresponds to approximately 1,200 MW of new generating capacity operating almost continuously, and is sufficient to meet the residential electricity needs of more than four million people. When intermittent energy sources such as wind are included, the total installed capacity will increase significantly over the target figure. Whilst the government has set the progressive targets for new capacity up to 2010, it has elected not to mandate that any part of the new renewable electricity must come from particular sources (Stucley and Robson, 2001).

There are a number of ways in which biomass can be used in order to generate electricity (Fung *et al*, 2000; Stucley and Robson, 2001; Zorretto and Chudleigh, 1999):

- direct combustion (such as coal fired power stations)
- co-firing with coal
- gasification (heating in the presence of oxygen to produce a combustible gas)
- pyrolysis (heating in the absence of oxygen to produce "bio-oil")
- cogeneration (production of both heat and power)
- production of liquid fuels (to power electrical generators) such as ethanol (fermentation process), methanol or higher molecular weight petrol-diesel hydrocarbons (Zerbe, 1992).

Markets

Current market size

In the late 1990s consumption of electricity in Australia stood at around 200,000 GWh (Zorretto and Chudleigh, 1999; Anon, 2000b). Data for consumption by State in Australia are summarised in Table 9 (ESAA, 2003). Around 20% of the consumption is by the energy generators and suppliers themselves. The consumption of electricity in Australia has grown by around 40% in the last decade.

Table 9: Electricity generation in Australia, 2000-2001 (GWh)

State	Electricity Generation (GWh)	Proportion of Total %
NSW / ACT	64,688	33%
VIC	49,971	25%
QLD	45,069	23%
WA	12,167	6%
SA	10,588	5%
TAS	10,113	5%
NT	1,651	1%
Other*	4,533	2%
Australia (total)	198,780	100%

*Snowy Mountains hydro-electric scheme

Future demand for electricity

It is estimated that for the foreseeable future demand for electricity in Australia will grow at a rate of about 2% per annum.

Feed-stocks and generating technology

Electricity production in Australia is dominated by the combustion of black and brown coal. Natural gas and hydroelectricity are also important. Considering Australia as a whole, 56% of electricity is generated from the combustion of black coal (NSW, QLD and WA), 28% from brown coal (VIC), 8.5% from hydro schemes (NSW, TAS and VIC) and 6.5% from natural gas (SA, WA and VIC). The small remaining quantities of electricity are generated by a variety of methods based on renewable resources, with the combustion of bagasse (sugar industry) and black liquor (Kraft pulp industry) being amongst the more important. Thus, when hydroelectricity is taken into account, some 10% of Australia's electricity is currently generated from renewable resources.

The abundant supplies of low cost, low sulphur containing coal in Australia make its energy amongst the cheapest in the world. Wholesale prices for electricity in Australia are around 2.8-3.5 cents/kWh (Fung *et al*, 2000; Anon, 2000b). Hydroelectricity has a low marginal generation cost, but the capital costs of building dams and establishing reservoirs and water catchments are high. Hydropower is used for meeting peak load requirements, since it can be rapidly started up and switched off. Natural gas is also used primarily for meeting peak load requirements, but systems based on gas are much slower in terms of their response compared with hydropower. Gas-fired electricity is also more expensive than coal-fired electricity. Table 10 shows the comparative costs of power generation from fossil fuels and some renewable sources.

In other parts of the world biomass and waste materials are used in significant quantities to generate electricity. For example, in the USA it is estimated that some 40,000 GWh / yr of electricity are generated from biomass other than municipal solid wastes (Hughes, 2000). This represents about 1% of the total electricity generated in the US. However, it is not clear to what extent these practices are subsidised.

Stucley and Raison (1999) reviewed the technologies that would be most suitable for generating electricity from biomass. For small plants i.e. those with continuous generating capacities of less than 1 MW, they concluded that boilers or gasifiers coupled with modified gas or diesel engines were the most appropriate. For larger installations, boilers or gasifiers coupled with turbines were deemed to be more suitable.

Table 10: Approximate costs for electricity generation for different energy sources (Fung *et al*, 2000)

Energy Source	Approximate cost (¢ / kWh)
Coal	2.8 - 3.5
Natural gas	4.5 - 6.5
Diesel	22 - 50
Biomass	5 - 15
Wind	5.5 - 8.5
Geothermal	5.6 - 18.5
Photovoltaics	40 - 80

In addition to different technologies being appropriate for different scales of biomass-based operation, Stucley and Raison (1999) also noted that there were likely to be strong economies of scale in terms of the estimated capital cost per unit output of electricity as plant capacities increased from 1 MW to 30 MW (see Table 11). It is worth noting though that even a 30 MW plant is still very small compared with typical coal-fired power stations, and that the associated capital cost per unit of generated electricity is consequently much higher. The efficiency of the boilers etc in biomass-based plants is also lower than coal fired boilers, owing to their smaller size and the typically higher moisture content of biomass materials.

Table 11: Capital costs for electricity generating plants based on woody biomass (Stucley and Raison, 1999)

Electrical Output (continuous)	Technology	Approximate capital cost (AU\$ / kW)
Under 10 kW	Boiler and engine	3,000
100kW	Gasifier and engine	2,900
1-5 MW	Boiler / turbine or gasifier / turbine	2,200 – 3,300
10-20 MW	Boiler / turbine or gasifier / turbine	1,600 – 2,000
20 MW and above (projected)	Gasifier and gas turbine	1,500
30 MW and above	Boiler and turbine	1,400

Stucley and Raison (1999) assumed that the raw material costs for small sized plants (less than 1MW) would be near zero, in particular where the electricity generation was associated with a wood processing industry (e.g. sawmill) where residues were used as feed material. Larger plants would require feed material to be transported to the plant site from surrounding areas. The cost of such material would vary depending on whether it was a largely unwanted waste or residue from another forest based operation, or whether it was actually in demand for use in other competing industries.

A 30 MW biomass-based operation located in a low rainfall region would require a plantation estate of around 50,000 ha dedicated solely to supplying its raw material requirements. The area required is equivalent to about 10% of the land area within 40 km of a power station. These estimates are based on coppiced biomass systems operating on 2 to 3 year rotations between harvests, dry biomass yields of between 5 and 7.5 tonnes / ha / annum and feedstock requirements of around 300,000 dry tonnes / annum.

However, such an operation would not currently be recognised as renewable energy, owing to the anomaly in the Renewable Energy (Electricity) Act which excludes electricity produced from woody biomass crops grown exclusively for energy generation from qualifying as part of the MRET. It has been argued (Bartle, 2001) that growing biomass solely for electricity generation is unlikely to be viable anyway, since the minimum price required by growers would make the total cost of electricity supply prohibitive. It follows therefore that biomass-based generating plants are more likely to be profitable if they use residues from other biomass processing industries. Not only would the feedstock be cheaper, but also the electricity produced would be eligible for MRET support. In this case, the economic size of the generating plant could be limited by the availability of suitable land to grow biomass crops within economic transport distances and / or the demand for electricity within an economic transmission distance.

Prospects

Owing to the abundant reserves of coal in Australia and their associated low costs, for the next decade at least the maximum potential market for new biomass derived electricity is likely to be that specified by the MRET. In order to encourage the uptake of renewable energy schemes, the MRET is providing a price premium of up to four cents per kilowatt hour. However, it is the consumers who will ultimately have to pay for the additional cost of renewably derived electricity, and the generating companies will certainly seek to identify the lowest cost options for meeting the MRET. This being the case, biomass-based electricity will have to compete with other forms of renewable electricity for a share of the market. It can be seen from Table 9 that, under favourable conditions, electricity generated from biomass is competitive with other forms of renewable energy.

In the next few years it is likely that the MRET will be met with a mixture of initiatives involving wind, hydro and biomass-based operations. A key factor in biomass-based electricity generation ventures will be the price of supply of feed-stocks. Preference will therefore be given to operations which can secure cheap sources of waste residues generated from other industries. One obvious source is likely to be the bark and sawdust residues from saw-milling, as these are the least sought after by other industries such as pulp, particleboard and MDF. However, opposition by some conservation groups to the use of mill waste from native (old and re-growth) forests could result in electricity produced from this source being excluded from the MRET, making its production uneconomic.

At present the two most promising technologies for processing biomass in the short to medium term appear to be gasification and co-firing (Stucley and Robson, 2001). Of the two, most progress has probably been made on co-firing. A number of feasibility trials in co-firing biomass at coal-fired power stations in Australia have been made, with some success. In the Upper Hunter Valley of NSW, Australia's largest electricity producer, Macquarie Generation, has conducted successful trials on the co-firing of sawdust (up to 5% by mass) with coal in the Liddell power station. However, large-scale implementation of co-firing in Australia has not been helped by difficulties in obtaining accreditation for this practice for renewable certification in NSW (Fung *et al*, 2000). Studies in Europe (Hartmann and Kaltschmitt, 1999) and North America (Hughes, 2000) into co-firing of biomass with coal have also suggested that the approach has promise. With modest coal substitution levels i.e. 10% or less, it is evident that boiler efficiency is only marginally reduced, the drop being attributable to the relatively high moisture content of biomass. The use of biomass also offers favourable advantages in terms of the total environmental impact of the generating process. However, it is still evident that the price of supply of biomass, and in particular transportation costs, could be a major barrier to the uptake of even co-firing of biomass (Noon and Daly, 1996).

A number of new initiatives involving biomass-based electricity generation have recently been announced as a result of the MRET. For example, technology developed by CSIRO is to be installed in a demonstration plant in Western Australia to produce electricity and high-value activated carbon (Fung *et al*, 2000¹; Anon., 2001a). This process will use fluidised-bed burners to partly reduce the wood to charcoal and simultaneously provide heat to produce steam for generating electricity. However, until the results of the study are known it is difficult to gauge what impact this technology could have on the ability for biomass-based electricity to supply a large part of the MRET. Other promising developments include plans for the construction of at least two further biomass fed power stations, one at Morwell in the La Trobe Valley, Victoria (Booth, 2001) and the other at Tarpeena, near Mt. Gambier, South Australia (Anon., 2001b). The Tarpeena plant is a A\$100M project commissioned by Auspine, designed to use 'in-house' wood residues from the company's saw mill operations. The plant at Morwell is a demonstration plant, designed to use a variety of feed-stocks including forestry residues, pulp waste, sludge and crop residues.

Although these announcements and initiatives are encouraging, it is also noteworthy that they are either demonstration plants, or are intended to burn essentially waste materials. Many of the technologies that could potentially be used to convert biomass to electricity are not proven and have yet to progress beyond the pilot scale. This is true for all regions of the world. Furthermore, it is clear that the straightforward combustion of biomass cannot compete economically with fossil fuels, particularly where significant returns are sought for the growing and supply of the biomass. These issues have already been analysed in some detail by Zorzetto and Chudleigh (1999). Their analyses suggest that even when biomass is available at near zero cost it is difficult to compete with coal.

Zorzetto and Chudleigh (1999) recognised that the cost of supplying electricity to non-metropolitan / rural regions of Australia is considerably higher than to the major towns and cities, due to the transmission costs. They argued therefore that reasonable economic cases could be developed for the generation of electricity in small stand-alone biomass-based plants located close to rural customers, either remote from base-load power stations, or off-grid. Such plants might have a generating capacity of around 1MW, with annual dry biomass requirements of around 10,000 tonnes.

Gas-fired microturbines for power generation is a new technology which might in the future play a larger role in utilising biomass in rural areas. Fuelling microturbines via the gasification process could for example make more efficient use of biomass. CSIRO is developing a small-scale gasification system to operate microturbine generators (Fung *et al*, 2000) in a size range of 35-200 kW_e. This is designed for distributive remote or regional power generation from wood wastes and sustainable biomass resources. One microturbine generator operating on natural gas, a fridge-sized unit manufactured in the US by Capstone, has been purchased and installed in Sydney for demonstration purposes. The unit generates about 30 kilowatts of electricity and allows for multiple units to be installed for increased output.

Conclusions

Stand-alone biomass fed electricity generating plants cannot currently economically compete with large coal-fired plants. Biomass-based plants must be necessarily smaller in capacity due to the likely dispersed nature of tree crops on agricultural land and the consequent greater costs associated with collecting and transporting biomass. They are consequently less efficient and both their fixed and variable costs are higher. The relatively high moisture content of biomass and its impact on efficiency is also a drawback.

Establishing a significant biomass-based electricity industry is particularly difficult in Australia because of its long established low cost coal-based industry. Supporting evidence for this view comes from recent experiences in the UK, where the fledgling biomass-based electricity industry has run into significant difficulties (Boyle and Edwards, 2002), despite the relatively high cost of fossil fuel based electricity generation. However, the MRET does offer a potential mechanism for the establishment of a biomass-based industry, particularly where biomass has cost advantages over other forms of renewable energy. Co-firing with coal in existing power stations appears to offer the most promise, though even here biomass will need to be readily available within the proximity of coal-fired stations to be viable. This places strict limitations on where biomass for co-firing could potentially be produced in low rainfall regions. Gasification is a technology with potential for biomass conversion, though more research is required before its merits can be fully evaluated.

It is believed that the best opportunities for biomass-based electricity generation in Australia lie in the utilisation of low / zero cost waste materials e.g. those produced by forest-based and other biomass-based industries. Given this, large scale plantings of woody crops in low rainfall regions dedicated to electricity generation would not appear to be a promising option, particularly where significant returns would be required for growing the crop. The current anomaly in the MRET legislation would in any case discourage the establishment of such an industry. Residues from woody crops could have more potential as a primary fuel source, since they are eligible for inclusion in the MRET in some circumstances. However, the distance of the key zones of demand for electricity from the sources of such crop residues significantly hampers the viability of large scale generating facilities.

Small-scale biomass-based electricity generating plants in rural areas possibly offer the best opportunity for conversion of low rainfall grown biomass. This is because of the high costs associated with servicing such areas using the national grid. However, the utilisation of low cost residues will still probably be necessary in order to make this a viable and attractive option. Given this, other viable industries based on woody biomass will need to be established.

Although it is difficult at present to justify the generation of electricity alone from biomass using strict economic criteria, it does nevertheless offer the potential for the consumption of significant amounts of biomass. For example, Bartle (2001) has estimated that if all of Australia's electricity demand was generated from biomass grown in WA, this would virtually solve the regions salinity problems at a stroke. It is clear, however, that such approaches could only be realised with significant involvement of the state and Federal governments i.e. legislative directives which go far beyond the current MRET, and a willingness by consumers to pay significantly more for their electricity.

Alcohols - ethanol and methanol

Introduction

Alcohols such as ethanol and methanol have long been known and used as fuels in vehicles. In the 1870's Nikolaus Otto, the co-inventor of the internal combustion engine, used ethanol to power his first engines; gasoline was not available as a fuel at that time. Even by the time Henry Ford produced his early Model-T vehicles, ethanol, or mixtures of ethanol and crude gasoline, were still considered viable as fuels. However, once the petroleum industry became firmly established world-wide, it became evident that ethanol simply could not compete with gasoline on a cost basis.

Although gasoline still has a cost advantage over ethanol, the latter is nevertheless currently used in many parts of the world as a fuel for sparked combustion engines. The drivers for this are varied. Ethanol is either co-blended with gasoline or used as a total replacement in modified engines. It is also used in a blend with diesel fuel to a very limited extent. Ethanol is produced predominantly from the fermentation of organic materials such as sugars and starches. It can also be produced from woody biomass. This, together with the enormous size of the global liquid fuels market has ensured that the subject of ethanol production from biomass has received a good deal of attention and research in recent years. The potential for establishing an ethanol industry based on biomass grown in low rainfall areas has been reviewed in some detail recently by Zorzetto and Chudleigh (1999). Few significant developments appear to have occurred since to alter their main conclusions.

Methanol is an important industrial intermediate for numerous chemicals. Formaldehyde is one of the more important chemicals produced from methanol, much of it being used in the manufacture of formaldehyde-based thermosetting adhesives. Methanol can also be used as a fuel in place of gasoline. For example, a number of classes of motor racing vehicle are powered by methanol. There is also interest in Australia and other parts of the world in the use of methanol in fuel cells in new future generations of vehicles. Although methanol is currently produced from natural gas by synthetic routes, it can potentially be produced from woody biomass via a variety of pyrolytic routes. However, the high toxicity of methanol (or more correctly the toxicity of the breakdown products of methanol once ingested by humans) is potentially a major stumbling block to the widespread adoption of methanol as a fuel.

Markets

World ethanol production in 1998 was estimated to be 33.3 billion litres, up from 28.7 billion litres in 1993 (Berg, 1999). The use of ethanol was divided into fuel (68%), industrial use (21%) and beverages (11%). In industry, ethanol is used as an industrial solvent and is the starting material in the production of acetaldehyde, acetic acid and methyl acetate amongst others. The main regions of the world where ethanol is used in significant quantities as a fuel are North and South America. The use of ethanol in South America is closely linked to the widespread availability of cane sugar as the feed-stock for ethanol production. A small proportion of the 'gasoline' in Australia is also comprised of ethanol / gasoline mixes. It should be noted, however, that where ethanol is used as a total replacement for gasoline in particular, significant subsidies are required in order to ensure its viability.

Based on figures quoted by Dong and Steinberg (1997), current world production of methanol is estimated to be around 45 million tonnes / annum. The market is still believed to be growing at around 10% / annum. Production of methanol in Australia is dominated by BHP Petroleum, which owns a 60,000 tonnes / annum production plant at Wyndham (20 km west of Melbourne) using ICI Advanced Gas Heated Reformer technology. The plant was commissioned in April 1995 at a cost of AU\$65 million. It supplies about 70 per cent of Australia's methanol requirements. The plant was originally a pilot scale facility to develop a larger production facility to utilise NW Australian shelf

gas fields. Recent announcements suggest that this latter facility, utilising natural gas as the feedstock, could soon be a reality. About 80 per cent of methanol in Australia is used for the manufacture of formaldehyde to produce urea, melamine and phenol formaldehyde adhesive resins.

Current consumption of gasoline and diesel in Australia is of the order of 32 billion litres / annum. This is predicted to increase to around 35 billion litres / annum by 2010. In theory, a significant proportion of this market could be satisfied by alcohols manufactured from biomass grown on low rainfall areas of Australia.

Production processes

Ethanol

Around 7% of ethanol is currently produced via synthetic routes. However the predominant method is fermentation. Around two thirds of the feedstock is based on sugar crops e.g. cane and beet, the remainder being derived from grain crops, principally maize. Grain feedstocks predominate in North America whilst sugar crops predominate in the rest of the world. Grain feedstocks require a hydrolysis pre-treatment in order to liberate the sugar molecules. Yeast (*Saccharomyces cerevisiae*) is used to ferment glucose and convert it to ethanol and carbon dioxide (which is collected as a by-product). The ethanol is then isolated by distillation of the fermentation liquor. Yeast cells are a rich source of protein and constitute another by-product of the fermentation process.

Production from woody biomass

The use of sugar and grain crops to manufacture ethanol is a key reason why ethanol struggles to compete on cost with gasoline. Both sugar and grain are in high demand in other market sectors, and consequently their cost is relatively high. It is because of this that there has been considerable interest in utilising other types of feedstock. Woody (lignocellulosic) biomass is one such option. Cellulose is typically the largest component of woody biomass and it is comprised of long chains of glucose molecules. It is thus eminently suitable as a feedstock for ethanol production. However, the other key components of biomass are lignin and hemicelluloses, which are either not suitable (in the case of lignin) or less suitable for ethanol production. Hemicelluloses are comprised of a range of sugars, which leads to a number of processing problems. For example, the hemicelluloses and cellulose hydrolyse at different rates, and over-reaction of the feedstock can lead to the production of degradation products which are unsuitable for ethanol manufacture. In addition, some of the sugars from which hemicelluloses are comprised are not fermentable with the standard organisms (yeast) used by the industry. The pentose sugars are known to present particular difficulties.

Duff and Murray (1996) extensively reviewed the key issues surrounding the bioconversion of forest residues to ethanol. They highlighted the fact that the chemical composition of woody tissue and the way that the key components were arranged together i.e. with the cellulose wrapped in hemicellulose and lignin sheaths, was a major hindrance to its efficient conversion to ethanol. To ensure that the bulk of the cellulose and to a lesser extent the hemicelluloses can be readily hydrolysed, it is therefore necessary to introduce an additional processing step into the production process for conversion of biomass to ethanol. This takes the form of a pre-treatment which is designed to breakdown the wood tissue and open up its structure. A variety of pre-treatments can potentially be used. These include organosolv, steam explosion, dilute acid pre-hydrolysis and ammonia fibre explosion. However, the organosolv treatment is only viable where there is market demand for the lignin by-products; as yet, such markets do not exist. This has been a key reason for the failure of the organosolv pulping process to become a commercial reality.

After the initial breakdown of the woody biomass to make its constituents more accessible, the next step involves the hydrolysis of the cellulose to break it down into individual glucose molecules. This process is also termed saccharification. A variety of methods can potentially be used to hydrolyse

the cellulose. These include treatment with either concentrated hydrochloric acid or dilute sulphuric acid (Scholler process), counter-current hydrolysis (a variant of dilute acid hydrolysis which is claimed to offer a potentially lower cost process) and enzymatic hydrolysis using cellulase (Duff and Murray, 1996). The efficiency of this particular process step has a significant bearing on the overall cost of the production process. It is evident that opinions on the merits of each approach vary widely between various interested parties e.g. research workers and development companies.

Once the cellulose has been hydrolysed to produce glucose, yeast is used in the conventional manner to ferment the sugar in solution ($\approx 4\%$ by mass) to produce ethanol, which is in turn isolated via distillation. Yeast is produced as a by-product. The quoted potential conversion efficiency of biomass to ethanol varies widely, with estimates of between 15 and 25% (Zorzetto and Chudleigh, 1999). Yields will be influenced by the type of treatments used and the composition of the input raw materials. Approximately 4-4.5% yeast (mass on input biomass), comprising 50% protein, is typically produced on completion of the fermentation process. Furfural and furfuryl alcohol may also be produced from pentose sugars produced during hydrolysis of biomass. Ready markets exist for these compounds.

The estimated production costs for ethanol from woody biomass vary considerably. Zorzetto and Chudleigh (1999) identified a number of studies which had attempted to estimate the likely cost of ethanol production from woody biomass. The analyses were based on hypothetical production plants with output capacities of around 50 million litres / annum or greater, with minimum raw material input requirements of 165,000 tonnes / annum of dry biomass. This is believed to be the minimum size of plant which would be economically viable. Estimates for likely production costs varied from AU\$0.48 to AU\$0.85 / litre. These estimates included raw material costs. This wide variation in estimated costs was attributable to the different technologies proposed for processing biomass, and different raw material types and costs. It is worth noting, however, that the estimated production cost of AU\$0.48 / litre (which is still around twice that of gasoline) assumed a conversion ratio of around 25%, which presumably must assume that at least a proportion of the pentose sugars are converted to ethanol. As far as is known such technology has yet to be proven, at least at a commercial scale.

In another assessment, Kaylen *et al* (2000) estimated that an optimum world-sized plant based on biomass would have an output capacity of 180 million litres / annum of ethanol and 330 thousand tonnes per year of furfural. Such a plant would require around 1.3 million tonnes of feedstock annually. The capital cost would be in the order of AU\$910 million for a 'green field' plant. In the study it was assumed that the feedstock would be primarily (agricultural) crop residues and 'some' woody biomass. The raw material costs were calculated to be approximately AU\$50 per tonne. The production costs for ethanol were estimated to be between AU\$0.31 and AU\$0.47 per litre.

Estimates by other workers regarding the likely costs of ethanol production reinforce the uncertainties currently surrounding the subject. For example, Foran and Mardon (1999) have suggested that using current technology the production cost for ethanol from biomass could actually be as high AU\$1.90 / litre. Foran and Mardon (1999) suggested that new processing technologies, coupled with markets for co-products, would be required in order to significantly reduce production cost of ethanol. They estimated that it might eventually be possible to produce ethanol at a cost of around AU\$0.35 / litre. This is supported by Duff and Murray (1996) who, citing Wyman (1994), suggested that a production cost of around AU\$0.65 / litre could be achieved with a simultaneous hydrolysis and fermentation process, coupled with 70% conversion of pentose sugars to ethanol.

Methanol

The current feedstock of choice for methanol production is natural gas. Methanol can also be synthesised from petroleum, coal and biomass. The normal synthesis process involves reforming of natural gas to synthesis gas (a mixture of hydrogen, carbon monoxide and carbon dioxide), and then

conversion to methanol via catalysis (Cr-Zn catalyst). However, the latest technologies are capable of converting natural gas directly to methanol without the need for the intermediate step.

Production from woody biomass

The alternative name for methanol is 'wood alcohol', being a by-product of charcoal production. The production of methanol from woody biomass is thus not a new concept. The destructive distillation of wood in pyrolytic reactors yields charcoal as the primary product, with approximately 1 to 2% yield of methanol. It is possible to increase the yield to almost 33% (Gullu and Demirbas, 2001) by the conversion of the biomass to "synthesis gas" (in the case of wood pyrolysis a mixture of hydrogen, carbon monoxide, methane, carbon dioxide and ethane) via gasification, followed by catalytic conversion to methanol. Further hydrogen is required to be fed into the synthesis gas to convert as much of the biomass carbon as possible to methanol carbon. A self-sustaining source of hydrogen is described in the HYNOL process where natural gas and wood biomass are used together as feedstock (Dong and Steinberg, 1997). These workers suggest that preliminary economic analyses indicate that the HYNOL process could be competitive with current industrial processes, citing a production cost of US\$0.114 / litre for a plant with an annual output capacity of 4,100 million litres. However, such a plant would require an annual input of around 1.6 million tonnes of dry woody biomass.

Prospects

The Australian government is keen to see an increase in the use of 'greener, cleaner' fuels such as ethanol, and to this end has set a target of using 350 million litres of biodiesel and fuel ethanol from renewable resources by 2010 and has initiated a new program 'Biofuels for cleaner transport', which will also provide capital subsidies to ethanol producers. There will thus likely be increased demand for ethanol as a fuel in the future. However, whether this demand can be met by an industry based on the processing of woody biomass in low rainfall regions of Australia is very difficult to assess. Any such industry would certainly face competition from a range of alternative sources of feedstock which would likely either be more suitable or cheaper.

Reference to the literature indicates that estimates of the likely costs of producing ethanol from biomass vary considerably. Even the most optimistic estimates give production costs which are around twice those of gasoline. Furthermore, these more optimistic estimates assume that raw materials can be supplied at very low cost, that processes which can convert pentose sugars to ethanol are commercially viable and that healthy demand would exist for by-products.

Given the above, it is believed that further work is required on the following before any case can be made for establishing a low rainfall biomass-based ethanol industry:

- development of proven technology for converting pentose sugars to ethanol
- identifying high value uses for the by-products of ethanol production.

There could also be merit in developing woody crops with high cellulose contents. Such work would have synergies with related forestry breeding studies targeted at the chemical pulp industry.

If the above could be addressed, and a low rainfall industry were proven to be viable, the benefits in terms of planted areas and amelioration of salinity could be highly significant. For example, Zorzetto and Chudleigh (1999) estimated that in low rainfall regions a plantation area of around 1 million hectares might be required in order to sustain just one 50 million litre / annum production facility. Their calculations were based on the assumption of relatively modest growth rates and that only a third of the woody biomass would be available to the ethanol plant. Using the growth rates proposed by Blakemore *et al* (2001) and Bartle (2001), and assuming all harvested woody biomass was

available for ethanol production, the planted area required for a sustainable operation might fall to as little as 100,000 hectares or less, with feedstock haulage distances of no greater than 20km.

Similarly to ethanol, the potential for an economically viable industry based on the conversion of woody biomass to methanol is very difficult to assess at present. The conversion technology developed to date is largely experimental. Whilst the claims by some researchers appear to offer some promise that a biomass-based process could compete with other processes and provide methanol at a price competitive with that of gasoline, large and extensive pilot scale studies are clearly required to fully evaluate proposed processes. Furthermore, it is not at all certain whether the scale of operations cited as necessary to keep unit production costs down would be viable in low rainfall areas. For example, a feed-stock requirement of the order of 1.5 million tonnes of dry woody biomass per annum for an individual plant would require significant planted areas of woody crops. A 'best case' scenario would probably be 500,000 hectares of woody crop planted on 15-20% of available land in a given area. Although transportation costs to the plant gate might be as low as \$10 / tonne of biomass, this could nevertheless make such an operation unattractive compare with one based on the utilisation of concentrations of residues and waste materials e.g. municipal waste.

It is worth noting that the key potential future market for methanol is likely to be for fuel cells in vehicles (rather than as a straight replacement for gasoline). At this point in time fuel cell technology is just one of a number of possible future technologies which are currently being investigated. Given this uncertainty, it must be highly questionable whether there should be significant investment in research into methanol production from low rainfall grown biomass.

Conclusions

Processing technology has yet to be developed and proven which can convert woody biomass to ethanol, such that the latter can compete 'on a level playing field' with liquid fuels derived from the petroleum industry. Even the most optimistic current estimates suggest that the production costs of ethanol would be double those of petrol. Accordingly, ethanol is only likely to be able to compete with petrol if it is made (at the very least partially) exempt from excise duties. This can probably only be contemplated at modest levels of petrol substitution.

In order to realise the full potential of ethanol from woody biomass grown in low rainfall regions it is believed that considerably more research is required on: technology to efficiently convert pentose sugars to ethanol; identification of markets for by-products; methods for producing biomass at very low unit cost efficiently and with tailored properties e.g. high cellulose contents.

It is believed that the current case for methanol is probably even more tenuous than that of ethanol. The known toxicity of methanol is likely to be a major barrier to its adoption as a fuel. In addition, the technology proposed for the conversion of biomass to methanol has yet to be fully proven, and the proposed scale of operation may well prohibit its application in low rainfall regions of Australia. Finally, fuel cell technology, which is considered to be the key potential future market for methanol, is still very much at an experimental phase.

It should be noted that the above conclusions hold for a stable international market in which petroleum and natural gas are plentiful and freely traded. However, should the market become unstable and supplies restricted, locally produced fuels such as ethanol could become increasingly attractive alternatives.

Pyrolytic bio-oil

Introduction

Pyrolytic bio-oil is one of the many terms used to describe the liquid that is produced from various pyrolytic treatments of woody materials. Other names used to describe the liquid product of wood pyrolysis include pyrolysis oil, bio crude oil, wood oil, wood liquids, liquid smoke, wood distillates, pyroligneous tar or acid, or simply liquid wood (Bridgwater *et al*, 1999). Typically, pyrolytic bio-oil consists of a complex mixture of organic compounds, with the precise composition varying with both the feedstock and pyrolysis process used. Where its yield is required to be maximised, fast or flash pyrolysis methods are usually employed, whereby small particles of biomass are subjected to high temperature in the absence of oxygen. This process very rapidly reduces the biomass structure to produce gases which condense to a mixture of organic liquids. The yield of liquid can be as high as 80% (by mass on the original mass of oven dry wood). Other by-products produced include solid char and non-condensing gases.

Bio-oil has a number of potential uses, though to date most attention has been focused on its potential as a fuel. In this respect, the key advantages that bio-oil is perceived to have over other bio-energy approaches (e.g. direct combustion of biomass and gasification) are that it can be stored and transported. Bio-oil can be used with coal to co-fire electricity generating plants, or in small-scale diesel engine power plants to generate electricity. It also has the potential to be mixed with diesel and used as a transport fuel. The complex nature of bio-oil and the diverse range of compounds from which it is comprised has also prompted researchers to investigate what value-added chemicals might be isolated from it. To date candidates for the speciality chemicals, food flavourings, pharmaceuticals, adhesives and wood preservation industries have been identified.

There are a number pilot scale facilities around the world dedicated to producing bio-oil, aimed at optimising its production primarily using various fast pyrolysis methods. It would appear that as yet, of the technologies under investigation, no clear front-runner has been identified.

Markets

The markets for electricity and transport fuels have been previously reviewed in the chapters focused on electricity from biomass and alcohols. With respect to transport fuels, bio-oil is only likely to be suitable as a partial substitute for diesel. Zorzetto and Chudleigh (1999) estimated demand for diesel fuel in Australia to be around 12 billion litres / annum in 1998 / 1999. However, penetration of the diesel market in Australia is not straightforward. A tax rebate system exists for diesel fuel used in rural areas ("off-road"). As of 1 July 2000 the rebate system extended to two new categories – marine and rail transport (ATO, 2000). The diesel fuel rebate now stands at 38 cents per litre and is regarded as a major disincentive for 'alternative' fuel development. Although a Diesel and Alternative Fuels Grants Scheme exists for trucks of 4.5 tonnes or more operating on public roads, a rebate of 18.5 cents per litre is available for diesel only.

A large number of individual compounds have been characterised and identified within bio-oil samples. A number of compounds remain unidentified. Some of the more common compounds identified to date include: acetic acid, formic acid, food flavourings, hydroxyacetaldehyde, levoglucosan, levoglucosenone (Gravitis *et al*, 2000), phenol and various phenol derivatives (e.g. resorcinol).

Compounds such as levoglucosan and levoglucosenone belong to a family of organic compounds called chiral synthons, having uses in the synthesis of pharmaceutical and biologically active compounds. It is claimed that they can comprise up to 20% (by mass) of the pyrolytic products of wood, and that they have a very high value e.g. AU\$20 - AU\$100 / gram (Trahanovsky, 1998).

However, it is not clear what the world demand for such products is, or what the costs might be to isolate them from bio-oil.

A major use for phenol is in the production of phenol formaldehyde (PF) adhesives, which are used in the wood composites industry as well as for foundry castings, friction materials and abrasive materials (as the binder). Phenol is also used in the preparation of Bisphenol-A (the feedstock for polycarbonates) and caprolactam (preparation of Nylon 6). Australian consumption of PF adhesives is estimated to be between 12,000 and 14,000 tonnes (100% solids basis) per annum, with a value of approximately AU\$80 million dollars. The price of phenol on the world market can fluctuate markedly between AU\$1.2 and AU\$2 / kg.

Production of bio-oil and applications

Production processes

The pyrolysis of wood can be carried out using a wide range of conditions, with key processing variables being exposure time, rate of heating and maximum temperature. The main products produced include charcoal, condensable organic liquids (bio-oil), tars and non-condensable gases. The liquids, tars and gases are comprised of a complex mixture of organic and aromatic compounds. Nan *et al* (1994) reviewed the range of technologies that are available for pyrolysing wood and biomass, and the main products which would be expected from each process (see Table 12).

Table 12: Key process conditions and products for various pyrolysis methods

Technology	Residence time	Heating rate	Temperature °C	Products
Carbonation	days	very low	400	charcoal
Conventional	5-30 min	low	600	oil, gas, char
Fast	0.5-5s	very high	650	bio-oil
Flash-liquid	< 1 s	high	< 650	bio-oil
Flash-gas	< 1 s	high	< 650	chemicals, gas
Ultra	< 0.5	very high	1000	chemicals, gas
Vacuum	2-30s	medium	400	bio-oil
Hydro-pyro.	< 10s	high	< 500	bio-oil
Methano-pyro.	< 10s	high	> 700	chemicals

The pyrolytic processes which fall within the 'fast' or 'flash' categories have received considerable attention in recent years. High yields of bio-oil can be obtained from these processes, and the bio-oil itself has a high 'energy density' (Nan *et al*, 1994) compared with other 'bio-energy' feed-stocks (see Table 13).

Table 13: Energy values from different biomass feedstocks

Feed	Bulk density (kg / m ³)	Heating value dry basis (GJ / tonne)	Energy density (GJ / m ³)
Straw	100	20	2
Wood chips	400	20	8
Bio-oil	1200	25	30
Charcoal	300	30	9
Char-water slurry	1000	15	15

Fast pyrolysis

The 'state-of-the-art' with respect to fast pyrolysis technology has been ably reviewed by Bridgwater *et al* (1999) and Scott *et al* (1999). Key features of a fast pyrolysis are:

- high heating and heat transfer rates; this is commonly facilitated by grinding the feedstock to a fine consistency
- carefully controlled reaction temperature of between 475 and 525^oC, with vapour residence times of 2 seconds or less
- rapid cooling of the vapours to yield the bio-oil product.

A wide range of fast pyrolysis reactor types have been investigated. Fluid bed type reactors have received considerable attention because they are relatively straightforward to operate and they are also seen to have good prospects for scale-up. Optimised processes utilise the char and non-condensable gas by-products for process heat, including drying of the feedstock to minimise the water content of the resulting bio-oil product.

The principal fast pyrolysis reactor technologies available today are:

- *Bubbling fluid beds*: These have been developed by several organisations and plants of various operating capacities (50 –200 kg / h) are being trialled by a number of organisations e.g. RTI Ltd, (Waterloo, Canada), Union Formosa (Spain), DynaMotive Energy Systems Corporation (Vancouver, Canada) and Wellman (UK).
- *Circulating fluid beds*: These have been developed to a commercial scale level most notably by Ensyn Technologies (Greely, Canada), using a system known as Rapid Thermal Processing (RTP™). Plants operate at several sites in the state of Wisconsin, USA. The largest plant, at Rhinelander, Wisconsin operates at a scale of 70 green tonnes / day and a second plant at Manitowoc (WI, USA) at 50 green tonnes / day (Sturzl, 1997). DynaMotive (Vancouver, Canada) operate a 10 tonnes per day plant. A larger 25 tonne per day commercial demonstration plant is stated to be planned for 2001 / 2002 which will serve as a springboard for the design and construction of a full scale 100 to 400 tonne per day commercial plant. The RTP™ process has been shown to be suitable for the processing of a large range of residues, including: sawdust, shavings, bark, sludges, agricultural wastes such as straw, bagasse and rapeseed cake, food processing residues (coconut shells, apple pomace, cellulosic casings), dried municipal sewage sludge, non-recyclable paper products and urban / industrial wood waste (pallets, crating, root / stump residues).
- *Ablative pyrolysis*: A key feature of this process is that much larger particle sizes can be processed using this technique. Principal proponents of this technology are NRTL (Colorado, USA) and CNRS (France).

Vacuum pyrolysis is another technique that has received some attention. It differs from other methods in that the rate of heating is very low, but the quality and yield of bio-oil is nevertheless achieved because the condensable vapours are removed as soon as they are formed. This is because the whole system operates under vacuum. One drawback cited for the technology is that it requires large scale equipment (Scott *et al*, 1999).

Owing to the fact that to date bio-oil production has largely been conducted experimentally on various scales of pilot plant, reliable data for the costs of bio-oil production are scarce. Data from operators of the few commercial facilities is also difficult to obtain. One equation (Ahnger and Graham, 1996; Bridgwater *et al*, 1999) which has been proposed as a guide for likely production costs of bio-oil from wood is as follows:

$$\text{Cost (LHV)} = [8.87 \times (\text{feedstock capacity})^{-0.3407}] + [(\text{feedstock cost}) \div (0.625 \times \text{Wood LHV})]$$

Where:

Bio-oil cost = ECU / GJ

LHV = Low Heat Value (GJ / tonne)

Feedstock capacity = dry tonnes / hour

Feedstock cost = ECU / dry tonne

The bio-oil energy yield is assumed to be 62%

The value for Wood LHV is taken as 19GJ / tonne.

Properties of bio-oil

Pyrolytic bio-oil is typically a dark brown liquid which will flow freely. However, its colour can vary from reddish to greenish depending on the feedstock, conversion process used and resulting composition. It normally consists of two distinct phases: an aqueous phase containing low molecular weight compounds and a non-aqueous phase made up of higher molecular weight aromatics. Its water content may vary from 15 up to 40%, which in turn influences its energy content and viscosity. Bio-oil has less than half the heating value of petrochemical fuels, with a typical value of 16-18 MJ / kg. The lower heating value of bio-oil is largely the result of its high water and oxygen content (up to 40% on an elemental basis). It is also relatively corrosive, due to the presence of carboxylic acids. On the plus side, bio-oil contains virtually no sulphur.

One important aspect of bio-oil is that it is relatively unstable. It will slowly decompose to char and other products even at room temperature. At higher temperatures this happens more rapidly. This limits what can be done to the product in terms of additional processing e.g. distillation to remove water or lighter organic fractions.

Although phenol and phenol derivatives (e.g. resorcinol) can be recovered from bio-oil, they are more generally recovered as a mixture of phenol and other neutral fractions. This can be a major draw-back to the demand for, and utilisation of, the material. Yields of the phenol / neutral compound from bio-oil can be approximately 30% based on bio-oil solids (Patents 1990). Higher recovery levels of phenolic compounds from bio-oils are possible if the pyrolytic feedstock is predominantly pine bark.

Applications

Electricity generation

The use of bio-oil as a fuel for electricity generation is currently seen as its main application. Two approaches are envisaged: co-firing in boilers and as a fuel for diesel engine power plants.

Co-firing bio-oil

Coal fired electricity generation offers the opportunity to co-fire with bio-oil with only minor changes to existing plants where liquid fuel spraying equipment is not present. The co-firing of bio-oil with coal has been performed successfully at the Manitowoc Public Utilities electricity generation plant in Wisconsin, USA since June 1987. Approximately 5% of the total fuel energy is provided by bio-oil. The bio-oil is produced from hardwood residues using Ensyn Technologies RTP™ technology, with a yield of 70-75% bio-oil. A portion of the bio-oil is extracted for value-added chemical products (unspecified) and the “residual” bio-oil is used for co-firing.

Combustion in diesel engine power plants

Bio-oil has been used in trials to fuel diesel engines for electricity generation (Bridgwater *et al*, 1999). A Wartsila V32 diesel engine (1.5 -6.5 MW power output), able to run on "alternative fuels", has been run on bio-oil generated using circulating fluidised bed technology. The diesel engine required a "pilot" fuel (gas oil or heavy fuel oil) for controlled combustion at a continuous level of 3-5% (wt. / wt.).

In this study an economic evaluation was performed based on an integrated production plant for bio-oil production coupled with electricity generation. A 6.5 MW power plant costing AU\$16 million was coupled with an RTP™ processing unit operating at about 110 (dry) tonnes / day of feedstock. The estimated cost of electricity generation was AU\$0.15 / kWh, assuming a feedstock cost of zero. The cost rose by about AU\$0.007 / kWh for every AU\$10 / (dry) tonne increase in feedstock cost.

Transport fuels

The use of bio-oil for transport fuels is a highly attractive option. However, as yet this does not appear to be economically viable. Ensyn Technologies Ltd of Canada, in collaboration with the Canadian government energy agency, claims to have developed a method of stabilising a bio-oil / diesel mixture using surfactants (the BDM Process™). However, there is no evidence that this product has been successfully commercialised.

A second approach for using bio-oil in transport vehicles is to enrich or upgrade the oil to a combustion energy level approaching that of diesel fuel. Enriching bio-oil removes water and oxygen at the same time adding hydrogen, leaving a petrochemical-like feedstock containing petrol, diesel and naphtha like mixtures. Methods such as fluid catalytic cracking, hydrothermal treatment and electronic or plasma-chemical upgrading can be used. However, this technology is still experimental and relatively expensive (Samolada and Vasalos, 1996).

Chemicals

The high market price of many pure chemicals makes the isolation of such compounds from bio-oil a potentially lucrative option. Three chemicals which can be generated by wood pyrolysis and which have generated some interest in the literature include the following:

- Hydroxyacetaldehyde (CH₂OH-CHO). This can be extracted from bio oil using methylene chloride. The aldehyde can be used in the production of hydrazones as oxygen scavengers in boiler water systems, has applications in reducing thermal and light-induced brightness reversion

in lignin-containing pulps and elimination of hydrogen sulphide by using water-in-oil emulsions (Radlein, 1999).

- Levoglucosan (1,6-Anhydro- β -D-Glucopyranose). This is a simplified monomer of cellulose and is a versatile chemical building block in the preparation of specialty polymers and resins, glucoside surfactants and non-hydrolysable polyglucoses.
- Levoglucosenone (6,8-dioxybicycl[3.2.1]oct-2-en-4-one). This is used in the synthesis of antibiotics and immuno-suppressive agents, the preparation of pheromones and in flavourings.

There are claims in the literature that 'phenol / neutral compounds' can be isolated from bio-oil at around half the market price of pure phenol, and that the extracted compounds can be used as direct substitutes for phenol in PF adhesives. However, whilst recent evidence (Chan *et al*, 2002) suggests that phenolic extracts from bio-oil *can* be used at phenol substitution rates of around 35% in PF adhesives, it is also clear that the performance of such 'substituted' adhesives is generally poorer.

It has been suggested that bio-oil, either in its natural state or specific fractions, could have applications as a wood preservative. This idea is not new. For example, in the past the liquid products of pyrolysis were used to preserve the hulls of wooden sailing crafts. However, it is highly questionable whether bio-oil would be approved as a wood preservative, given its toxicity (similar to creosote), variability and likely propensity to be leached from wood products in service.

There are numerous other compounds which could potentially be derived from bio-oils. However, just because certain compounds are present in bio-oil, it does not automatically follow that a lucrative chemicals industry can be based on bio-oil. The main factor which is likely to prevent a bio-oil based chemicals industry becoming a reality is the high cost of separating the compounds from each other, particularly where very high purity is required. The separation of compounds in bio-oil is made more difficult (and therefore more costly) because of the sheer number of compounds comprising the liquid, and its relative thermal instability.

The changes which have occurred in the coal industry serve to demonstrate the difficulties a bio-oil based chemicals industry could have in attempting to establish itself. Phenol occurs naturally as one of a number of compounds in certain coal products, and was traditionally derived from coal via distillation. However, almost all phenol is now chemically synthesised from benzene derived from the cracking of crude oil, for the simple reason that the synthetic route is lower cost.

Prospects

Industries based on the pyrolysis of woody biomass to generate bio-oil are an attractive option for low rainfall regions of Australia. It is evident that a wide range of lignocellulosic residues could be utilised in the pyrolysis process, including leaves and bark as well as woody material. Furthermore, small scale pyrolysis units could be established to initially produce the bio-oil. The bio-oil could then be utilised as a fuel in the same locality to generate electricity on a small scale e.g. in diesel engines, or it could be transported to a central point for larger scale electricity generation. Furthermore, if the appropriate technology is developed, there is the prospect that bio-oils could be further processed into transport grade fuels or separated into a range of value added chemicals.

However, there are a number of current barriers to the establishment of a low rainfall bio-oil industry. The production of bio-oil has apparently yet to be fully proven at a commercial scale, despite the fact that bio-oil appears to have been utilised in at least one electricity generating plant in Canada for a number of years. It is likely that this activity has been generously subsidised. The current estimated cost of electricity generation via small-scale bio-oil fuelled diesel engines also appears expensive compared with that of coal-fired electricity. Major technical advances are also required in order to economically upgrade bio-oil to transport fuel grade or to fractionate the oil into value-added pure compounds.

Conclusions

Further research into the following is required in order to make a low rainfall industry based on pyrolytic bio-oil a reality:

- optimisation of the pyrolysis process
- evaluation of the influence of raw material type on process economics and bio-oil composition
- technology to economically upgrade bio-oil to transport grade fuel
- technology to economically fractionate bio-oil into pure value added compounds.

Summary and conclusions

The products investigated were:

- appearance grade timber
- dry formed fibreboard
- wood-plastic composites
- electricity from woody biomass
- alcohols – ethanol and methanol
- pyrolytic bio-oil.

The above products fall into two distinct groups. Appearance grade timber, fibreboard and wood plastic composites are encompassed within the traditional or emerging forest products industries. The remaining products are concerned with the energy and chemicals industries which are large, challenging markets currently dominated by fossil fuels and synthetic chemicals.

Each of the previous chapters within this report has reviewed markets, processing and development needs for a product, and includes a conclusions section. This chapter provides a summary of key conclusions on products, together with recommendations for research and industry development. An overall conclusion and recommendation is given at the end.

Appearance grade timber

Hardwoods grown in low rainfall areas would have suitable properties for the non-structural sawnwood and veneer market. It is estimated that the current market for sawn hardwood timber in Australia is of the order of 1.1 million m³ / annum, and that at least half of this is appearance grade. Predictions are that the market will decline gradually to the year 2010, and thereafter increase to around 1.3 million m³ / annum. In the future, the market will be dominated by appearance grade products. A potentially sizeable market for appearance grade products also exists in Japan, though careful selection of appropriate timbers would be required to realise significant market penetration. On the other hand, significant expansion in hardwood plantation resources and associated processing industries is anticipated in other parts of Asia. This could have a significant impact not only on the shape and composition of overseas markets, but also the domestic Australian market. The extent of the expansion of hardwood plantations in higher rainfall regions across Australia will also be a factor in determining the future for low rainfall grown hardwoods.

It is believed that any sawmill constructed to process low rainfall grown timbers would need to have a minimum input capacity of 30,000 m³ / annum of logs in order to be economically viable. Such a mill would require around 20,000 hectares of forest to provide the necessary feedstock. It is estimated that production costs could be as low as AU\$320 / m³ of kiln dried sawn product, with input raw material costs adding a further AU\$180 in cost to every cubic metre of sawn product. However, these costs assume the 'best case' for many processing variables e.g. log and haulage costs, log quality, drying costs and sawn wood recovery rates. 'Worst case' estimates suggest that production costs could be almost double at around AU\$610 / m³, with raw material costs adding at least another AU\$240 in cost to every cubic metre of sawn product. It has also been suggested that costs could be markedly reduced if mill capacities and the level of technical sophistication were significantly increased. However, it is uncertain whether such approaches would be viable for processing hardwoods grown in dispersed lots in low rainfall regions.

The key drawback to establishing an economically viable industry is that current hardwood growth rates in low rainfall areas are believed to be too low. Accordingly, advances will need to be realised in the following areas: genetic improvements to increase growth rate, form and branching habit; improved silvicultural management to produce larger diameter stems; drying strategies and schedules developed and optimised for low rainfall species; improved understanding of gluing, machining and

stability attributes. Furthermore, markets will need to be found for sawing residues and small roundwood.

It is believed that penetration and capture of markets equating to around half of the current domestic Australian market for non-structural hardwood timbers by low rainfall grown appearance products is probably optimistic. In such a scenario, the land area required for a sustainable plantation-based industry would probably amount to less than 1% of the 80 million hectares in salinity-prone agricultural regions in Australia. However, this would still be an industry of significant size. For example, if suitable, the sawing residues and small roundwood from such an industry would be sufficient to supply a dry formed fibreboard industry at least twice the size of the current Australian industry.

Dry formed fibreboard

A substantial future potential export market exists for Australian produced MDF in the Asia-Pacific region. Predicted future growth in demand over the next decade alone equates to the output of between 3 and 7 modern production plants in each successive year. It is estimated that the wood raw material requirements for the entire Asia-Pacific MDF market by the year 2010 would require a planted area in excess of 3 million ha in low rainfall regions. However, likely strong competition from other producers in the region i.e. New Zealand, South East Asia, based on low-cost high rainfall grown resources, and possibly also recycled wood and agri-residues, will severely limit potential market sizes. It is suggested that a realistic goal for any future low rainfall zone MDF industry is probably around 10% market penetration, which would require approximately 500,000 ha of plantation area in order to sustain it, i.e. 0.6% of the total area of agricultural land in the salinity zone. In order to realise such a goal, substantial R&D efforts will be required to develop radical new approaches to generating low cost woody biomass with the appropriate properties.

Wood-plastic composites

Wood-plastic composites (WPCs) are new products which have shown strong growth in recent years in North America; sales of WPCs exceeded 300,000 tonnes in 2000, and the market is predicted to double in size by 2005. WPCs are used in a variety of applications, primarily windows, decking, siding, cladding, mouldings and architrave, and directly substitute materials made from either wood or plastic alone. Compared with wood-based materials they offer improved dimensional stability and resistance to biodegradation. In the case of plastics they offer potential cost savings. Production costs for HDPE WPCs are estimated to vary between AU\$900 and AU\$2050 / tonne of product, depending on the relative proportions of wood and plastic used in the product, the type of plastic used (virgin or recycled) and the form of the wood used (chip, flake or flour). A typical individual extruder or extrusion system might have an output capacity of between 500kg and 1 tonne / hour of product. Accordingly, a small production facility might only require as little as 500 tonnes of dry woody biomass per annum.

It is believed that WPCs represent a potential option for utilising woody biomass grown in low rainfall areas of Australia. In terms of value, potentially sizeable domestic and export markets exist for the products. The WPC industry in Australia is currently in its infancy. It is estimated that a market size of 50,000 tonnes per annum of product could exist in 2010, with a value of AU\$200 million. The drawback is that when viewed in isolation, the planted land area required to provide the wood feedstock for such an industry would be negligible in the context of the total land area in the salinity zone. However, the relatively small scale of production units, the modest associated investment costs, and the fact that residues from (low rainfall) saw-milling operations might be suitable are attractive features of WPCs.

In order to fully evaluate the prospects for a low rainfall based WPC industry, further work is required to determine the likely performance of the products in Australian and other sub-tropical environments. Work is also required to determine the relative suitability of woody residues from low

rainfall regions for WPCs compared with residues derived from high rainfall based operations and urban environments e.g. recycled wood.

Electricity from biomass

Annual consumption of electricity in Australia is around 200,000 GWh, and this is predicted to grow at about 2% / annum for the foreseeable future. Eighty five percent of Australia's electricity is generated by the combustion of coal. The remainder comes predominantly from the combustion of gas and hydropower. The latter currently represents the key source of Australia's renewable electricity. In 2003, the mean production cost of electricity from coal is around AU\$0.03 / kWh.

A variety of methods exist for the generation of electricity from biomass. Of these, co-generation (combustion with coal in existing power stations) and gasification appear to offer the most promise at present. The benefits of the former are the savings in capital costs, whilst the latter offers potential efficiency improvements. However, even when the biomass is available at near zero cost, with current technology it is not feasible to generate and supply electricity at a similar cost to that of the coal-based industry. Biomass-based plants must be necessarily smaller in capacity due to the greater costs associated with transporting biomass. They are consequently less efficient and both their fixed and variable costs are higher. The relatively high moisture content of biomass and its impact on efficiency is also a drawback. In 2003, figures for the most favourable estimates for the cost of production of biomass based electricity were around AU\$0.05 / kWh.

The Australian Federal Government introduced an Act for an additional 2% Mandatory Renewable Energy Target (MRET) which will require an additional 9,500 GWh / year of electricity to be produced from renewable sources. This aims to raise Australia's electricity generation from renewable resources to approximately 12% of the total by 2010. The MRET offers a potential mechanism for the establishment of a biomass-based industry, particularly where biomass has cost advantages over other forms of renewable energy e.g. wind and solar.

Although an 'anomaly' in the MRET legislation prevents plantations being established solely for bioenergy production, it is believed that for the foreseeable future any biomass-based electricity generation is in any case likely to be based on various waste streams from a variety of industries e.g. forestry and agriculture. This is because of the likely lower cost of such feed-stocks. Opportunities for large-scale plantings in low rainfall areas aimed solely at providing feed-stocks for the electricity generating market, thus appear to be limited. Residues from low rainfall crops could have more potential as a feedstock. However, in this case the potential size of any electricity generating industry would effectively be limited by the size of any other low rainfall industries based on the primary feed-stocks.

The high costs associated with servicing the electricity needs of the rural areas of Australia offer one possible opportunity for low rainfall grown biomass. In this case small-scale biomass-based electricity generating plants could be economically viable. Such plants might typically have generating capacities of around 1 MW with annual inputs of around 10,000 tonnes of dry biomass. However, the utilisation of low cost residues would still probably be necessary in order to make this an attractive option; this is likely to be true even without the current MRET anomaly. Given this, other viable industries based on woody biomass would still need to be established.

Alcohols - ethanol and methanol

Ethanol can be produced from woody biomass and can be used as a substitute liquid fuel for gasoline. As such, the domestic (and indeed export) market for ethanol derived from woody biomass is potentially very large. However, processing technology has not yet been developed and proven which can convert woody biomass to ethanol, such that the latter can compete on a straight economic basis with gasoline. Estimates of the likely costs for producing ethanol from biomass range from AU\$0.48 / litre to around AU\$1.90 / litre. The large variation in estimated costs stems from

differences in scale of operation, type and cost of feedstock and the proposed processing technology. Significantly, the lower estimated costs are associated with the larger operations, with assumed low feedstock costs and high biomass to ethanol conversion ratios using largely unproven technology.

It has been estimated that the minimum size of ethanol plant, which could be economically viable, would have an output capacity of around 50 million litres / annum, and raw material input requirements of 165,000 tonnes / annum of dry biomass. The planted area in low rainfall regions required to sustain such an industry could range from 100,000 to 1 million hectares, depending on achievable growth rates, and the range and type of competing / synergistic industries in the same region. A low rainfall ethanol industry could thus have a significant effect on salinity. However, for this to become a reality, a number of further developments will be required. Firstly, efficient and proven methods for the conversion of pentose sugars to ethanol need to be found. The identification of viable markets for by-products would also significantly reduce costs. These latter requirements apply equally to all potential ethanol initiatives. From a low rainfall perspective, approaches will also need to be found which facilitate the production of biomass at very low unit cost and possibly also with tailored properties e.g. high cellulose contents.

Much of the methanol currently produced in the world is used for the production of other chemicals e.g. formaldehyde, for use in thermosetting adhesives. However, similarly to ethanol, methanol can be used as a substitute liquid fuel for gasoline. It also has the potential to be used in fuel cells, a technology which is currently being developed and assessed for vehicles of the future. Consequently, potentially very large markets exist for methanol. Methanol is currently produced from natural gas. However, it can also be derived from woody biomass (this is not a new concept; methanol is often referred to as 'wood alcohol' in many text books).

Traditional methods of producing methanol from wood only give yields of around 1-2%. However, it is possible to increase yields to over 30% by the conversion of the biomass to "synthesis gas" via gasification, followed by catalytic conversion to methanol. Further hydrogen is required to be fed into the synthesis gas to convert as much of the biomass carbon as possible to methanol carbon. One process, the so-called HYNOL process, is claimed to be able to produce methanol at a cost which is competitive with gasoline e.g. of AU\$0.22 / litre. However, the scale of processing plant required is large, having an annual output capacity of over 4,000 million litres of methanol and an annual input of around 1.6 million tonnes of dry woody biomass. It is estimated that an individual plant would require planted areas in low rainfall regions well in excess of 1 million hectares in order to service its feedstock requirements. However, the haulage costs alone for such an operation could be prohibitive if the planted areas were widely dispersed. Its suitability for low rainfall regions must therefore be highly questionable.

Pyrolytic bio-oil

Pyrolytic bio-oil is the liquid that is produced from various pyrolytic treatments of woody materials. Bio-oil typically consists of a complex mixture of organic compounds, with the precise composition varying with both the feedstock and pyrolysis process used. Fast (or flash) pyrolysis methods are used to maximise the yield, which can be as high as 80% (by mass on the original mass of oven dry wood).

Bio-oil has a number of potential uses, including: a fuel for electricity generation; transport fuels; a source of value-added chemical compounds e.g. for the speciality chemicals, food flavourings, pharmaceuticals, adhesives and wood preservation industries. To date most attention has been focused on its potential as a fuel for electricity generation. It has apparently been utilised for a number of years in at least one coal-fired electricity generating plant in Canada. Despite this, however, bio-oil is still largely at the pilot scale of its development process, with the merits of at least three technologies currently being evaluated by various research groups around the world. One draw-back of bio-oil is that it has less than half of the fuel energy content of petrochemical fuels, owing to its high water and oxygen content. Technology exists to upgrade bio-oil to transport grade

fuel, but it is too expensive to be competitive with petrochemically derived diesel. Similarly, whilst bio-oil has been shown to be comprised of a large number of value-added compounds, technology has yet to be identified to facilitate their economic separation.

It is believed that whilst a low rainfall industry based on small-scale biomass pyrolysis units has many attractions, research into the following is required in order to make it a reality: optimisation of the pyrolysis process; evaluation of the influence of raw material type on process economics and bio-oil composition; technologies to economically upgrade bio-oil to transport grade fuel and to fractionate bio-oil into pure value added compounds.

Conclusions and recommendations

Table 44 summarises estimated production cost data and feedstock requirements for 'typical' production facilities for each of the target products analysed in this review.

The estimated production costs for target products are exclusive of wood raw material costs, and it is believed that they are not likely to vary significantly between different (rainfall) regions. The wood raw material costs will thus be crucial to the economic viability of the production processes in a low rainfall environment. Evidence suggests that currently it is probably not possible to produce and supply woody feedstock cheaply enough in low rainfall regions to compete with either similar feedstocks grown in higher rainfall regions or fossil fuel feedstocks. This suggests that future R&D efforts should be predominantly focused on improving the germplasm and silviculture of selected, promising woody perennials, as well as novel harvesting approaches, in order to improve the quality and yield of feedstocks and significantly reduce the delivered cost of raw materials to a competitive and attractive level.

Table 44: Summary of key production cost data and feedstock requirements for target products (based on 2003 data)

Product	Total Production Cost*	Raw material requirements for a typical production facility (annual)**
Appearance grade timber	AU\$320 - AU\$610 / m ³	30,000 m ³
MDF	AU\$205 / m ³	75,000 tonnes
Electricity from biomass	AU\$0.05 / kWh	10,000 tonnes
Ethanol	AU\$0.31 - AU\$1.50 / litre	165,000 tonnes
Methanol	AU\$0.18 / litre	1.6 million tonnes
HDPE Wood Plastic Composite	AU\$900 - AU\$2050/tonne	5,000 tonnes
Electricity from Pyrolytic bio-oil	AU\$0.15 / kWh	40,000 tonnes

*Excluding wood / biomass raw material cost

**Mass values are for oven dry material

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