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Biomass resource facilities and biomass conversion processing for fuels and chemicals

Ayhan Demirbaş *

P.K. 216, TR-61035-Trabzon, Turkey

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Abstract

Biomass resources include wood and wood wastes, agricultural crops and their waste byproducts, municipal solid waste, animal wastes, waste from food processing and aquatic plants and algae. Biomass is used to meet a variety of energy needs, including generating electricity, heating homes, fueling vehicles and providing process heat for industrial facilities. The conversion technologies for utilizing biomass can be separated into four basic categories: direct combustion processes, thermochemical processes, biochemical processes and agrochemical processes. Thermochemical conversion processes can be subdivided into gasification, pyrolysis, supercritical fluid extraction and direct liquefaction. Pyrolysis is the thermochemical process that converts biomass into liquid, charcoal and non-condensable gases, acetic acid, acetone and methanol by heating the biomass to about 750 K in the absence of air. If the purpose is to maximize the yield of liquid products resulting from biomass pyrolysis, a low temperature, high heating rate, short gas residence time process would be required. For high char production, a low temperature, low heating rate process would be chosen. If the purpose is to maximize the yield of fuel gas resulting from pyrolysis, a high temperature, low heating rate, long gas residence time process would be preferred. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

There are many different ways in which the abundance of energy around us can be stored, converted and amplified for our use. Energy sources will play an important role in the world's

* Tel.: +90-0462-248-7429; fax: +90-0462-248-7344.

E-mail address: ayhandemirbas@hotmail.com (A. Demirbaş).

future. The energy sources have been split into three categories: fossil fuels, renewable sources and nuclear sources. The fossil fuels are coal, petroleum and natural gas.

The point where the cost of producing energy from fossil fuels exceeds the cost of biomass fuels has been reached. With a few exceptions, energy from fossil fuels will cost more money than the same amount of energy supplied through biomass conversion. Biomass is the term used to describe all biologically produced matter. World production of biomass is estimated at 146 billion metric tons a year, mostly wild plant growth [1].

The renewable energy sources are solar, wind, hydroelectric, biomass and geothermal power. The nuclear powered sources are fission and fusion.

Biomass is the name given to all the earth's living matter. It is a general term for material derived from growing plants or from animal manure (which is effectively a processed form of plant material). It is a rather simple term for all organic material that stems from plants (including algae), trees and crops. Biomass energy is derived from plant and animal material, such as wood from natural forests, waste from agricultural and forestry processes and industrial, human or animal wastes.

Plants absorb solar energy, using it to drive the process of photosynthesis, which enables them to live. The energy in biomass from plant matter originally comes from solar energy through the process known as photosynthesis. The energy, which is stored in plants and animals (that eat plants or other animals), or in the wastes that they produce, is called biomass energy. This energy can be recovered by burning biomass as a fuel. During combustion, biomass releases heat and carbon dioxide that was absorbed while the plant was growing. Essentially, the use of biomass is the reversal of photosynthesis. Is biomass energy a variety of chemical energy? In nature, all biomass ultimately decomposes to its molecules with the release of heat. The release of energy from the combustion of biomass imitates natural processes. Therefore, the energy obtained from biomass is a form of renewable energy and, in principle, utilizing this energy does not add carbon dioxide to the environment, in contrast to fossil fuels [2]. Of all the renewable sources of energy, biomass is unique in that it is effectively stored solar energy. Furthermore, it is the only renewable source of carbon and is able to be converted into convenient solid, liquid and gaseous fuels [3].

Biomass can be used directly (e.g. burning wood for heating and cooking) or indirectly by converting it into a liquid or gaseous fuel (e.g. alcohol from sugar crops or biogas from animal waste). The net energy available from biomass when it is combusted ranges from about 8 MJ/kg for green wood, to 20 MJ/kg for dry plant matter [4,5], to 55 MJ/kg for methane, as compared with about 27 MJ/kg for coal [2].

Many biomass fired electricity generators use waste materials, such as straw or domestic refuse. Other schemes are based on the idea of cultivating crops of various kinds, especially to provide biomass for fuel.

2. How important is biomass?

Biomass, mainly in the form of wood, is the oldest form of energy used by humans. Traditionally, biomass has been utilized through direct combustion, and this process is still widely

used in many parts of the world. Biomass has historically been a dispersed, labor intensive and land intensive source of energy. Therefore, as industrial activity has increased in countries, more concentrated and convenient sources of energy have been substituted for biomass.

Biomass, mainly, now represents only 3% of primary energy consumption in industrialized countries [6]. However, much of the rural population in developing countries, which represents about 50% of the world's population, is reliant on biomass, mainly in the form of wood, for fuel. Biomass accounts for 35% of primary energy consumption in developing countries, raising the world total to 14% of primary energy consumption [6].

The earth's natural biomass replacement represents an energy supply of around 3000 EJ (3×10^{21} J) a year, of which just under 2% is currently (1998) used as fuel. It is not possible, however, to use all of the annual production of biomass in a sustainable manner. One analysis provided by the United Nations Conference on Environment and Development (UNCED) estimates that biomass could potentially supply about half of the present world primary energy consumption by the year 2050 [6].

Biomass has great potential as a renewable energy source, both for the richer countries and for the developing world. Biomass as a fuel is still in the experimental stage and provides only about 0.25% of the total electricity generating capacity in the UK. However, this is likely to increase for a number of reasons. One reason is that European and UK legislation aims to encourage less polluting methods of waste disposal, and one viable option is to burn the waste to generate power. Another reason is that biomass power systems will become more affordable as the technology improves.

Biomass is used in a similar way to fossil fuels, by burning it at a constant rate in a boiler furnace to heat water and produce steam. Pipes carry the steam through the furnace again to raise its temperature and pressure further, and then, it passes through the multiple blades of a turbine, spinning the shaft. The turbine shaft drives an electricity generator which produces an alternating current for use locally or to supply the national grid.

Liquid biofuels, such as wheat, sugar, root, rapeseed and sunflower oil, are currently being used in some member states of the European Union, like Austria, Belgium, France, Germany, Italy and Spain [7].

Refuse fuels used in power stations would otherwise have to be disposed of in landfill sites or in some other way. Efficient burning reduces them to a relatively small volume of ash while also producing useful electricity or heat energy.

There are also potential benefits in growing biomass especially for fuel. Provided the right crops are chosen, it is possible to use poor quality land which is unsuitable for growing food.

Burning biomass produces some pollutants, including dust and the acid rain gases sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Burning wood produces 90% less sulfur than coal. These can all be reduced before releasing the fuel gases into the atmosphere. At the present rate of use, the quantities of atmospheric pollution involved are insignificant compared with other pollution sources, but this would be a factor to consider if the use of biomass increased.

Carbon dioxide (CO_2), the greenhouse gas, is also released. However, as this originates from harvested or processed plants, which have absorbed it from the atmosphere in the first place, no additional amounts are involved.

3. Biomass energy

Biomass energy is one of humanity's earliest sources of energy. Biomass is used to meet a variety of energy needs, including generating electricity, heating homes, fueling vehicles and providing process heat for industrial facilities. Biomass potential includes wood and animal and plant wastes. Biomass is only an organic petroleum substitute which is renewable. The term 'biomass' refers to forestry, purposely grown agricultural crops, trees and plants and organic, agricultural, agro-industrial and domestic wastes (municipal and solid waste) [8]. Biomass is the name given to the plant matter which is created by photosynthesis in which the sun's energy converts water and CO_2 into organic matter. Thus, biomass materials are directly or indirectly a result of plant growth. These include firewood plantations, agricultural residues, forestry residues, animal wastes etc. Fossil fuels can also be termed biomass, since they are the fossilized remains of plants that grew some millions of years ago.

The one renewable energy source on which mankind has relied since the discovery of fire is photosynthesis, the process in which solar energy is converted into an energy rich biomass. In this process, solar energy, absorbed by green plant tissue, provides energy to reduce CO_2 and form carbohydrates which are then utilized as energy sources and raw materials for all other synthetic reactions in the plant. Thus, solar energy is captured and stored in the plant, thereby providing food, fiber, fuel and shelter for mankind. However, this photosynthesis uses only a small portion of the sun's energy to fix 200 billion tons of carbon into terrestrial and aquatic biomass with an energy content of 3000 billion GJ/y. Yet, only 1/10th of the world's biomass energy is consumed, while the rest is left untapped [9]. Every year, plants store 10 times the present annual consumption of energy. This large quantity of energy can not only contribute to the country's energy resources but also can effectively provide a wide range of chemical feed stocks for the organic chemical industry, thus saving the consumption of precious non-renewable petroleum products. Moreover, it is environmentally friendly and prevents ecological imbalance. Stored plant energy can be utilized by burning it directly or using various processes to obtain potential fuels, such as ethanol, methane etc.

Forest energy involves the use of forest biomass which is currently not being used in the traditional forest products industries. Essentially, this means the forest residues left after forest harvesting, residual trees and scrub or under-managed wood land. Forest residues alone count for some 50% of the total forest biomass and are currently left in the forest to rot [10].

The opportunity to combine fuelwood production with effluent disposal has many potential environmental benefits. The economic feasibility of woody biomass plantations is difficult to justify at present, but if full costing of externalities, such as CO_2 emissions, are to be applied in the future, then acceptable payback periods for boiler conversions and handling and storage facilities could be achieved.

4. Resources of biomass

Biomass resources include wood and wood wastes, agricultural crops and their waste by-products, municipal solid waste (MSW), animal wastes, waste from food processing and aquatic plants and algae. The average majority of biomass energy is produced from wood and wood wastes (64%), followed by MSW (24%), agricultural waste (5%) and landfill gases (5%) [7].

Biomass is the oldest known source of energy. Biomass is a renewable source. It supplies only 4% of the industrialized countries' energy. Biomass energy comes from burning organic matter. Biomass is burned in a special waste to energy plant to produce electricity. Biomass fuel comes from landfills and agricultural waste. In landfills, a gas called methane is used as a fuel in waste to energy plants. Energy from biomass costs more than coal. Burning waste for energy reduces 60–90% of the trash dumped in landfills. This also reduces landfill cost.

Biomass differs from other alternative energy sources in that the resource is varied, and it can be converted to energy through many conversion processes. Biomass resources can be divided into three general categories:

1. wastes
2. standing forests
3. energy crops

Biomass resources that can be used for energy production cover a wide range of materials. Biomass energy can be separated into two categories, namely modern biomass and traditional biomass. Modern biomass usually involves large scale uses and aims to substitute for conventional energy sources. It includes wood and agricultural residues, urban wastes and biofuels, such as biogas and energy crops. Traditional biomass is generally confined to developing countries and small scale uses. It includes fuelwood and charcoal for domestic use, rice husks and other plant residues and animal wastes. Examples of biomass energy resources are:

Wastes:

- agricultural production wastes
- agricultural processing wastes
- crop residues
- mill wood wastes
- urban wood wastes
- urban organic wastes

Forest products:

- wood
- logging residues
- trees, shrubs and wood residues
- sawdust, bark etc. from forest clearings

Energy crops:

- short rotation woody crops
- herbaceous woody crops
- grasses
- starch crops (corn, wheat and barley)
- sugar crops (cane and beet)
- forage crops (grasses, alfalfa and clover)
- oilseed crops (soybean, sunflower, safflower)

Aquatic plants:

- algae
- water weed
- water hyacinth
- reed and rushes

The demand for energy is increasing at an exponential rate due to the exponential growth of world population. This, combined with the widespread depletion of fossil fuels and gradually emerging consciousness about environmental degradation, suggests that the energy supply in the future has to come from renewable sources of energy. Statistics show that, although total renewables now account for nearly 18% of global primary energy supply, out of this, over 55% is supplied by traditional biomass and about 30% by large hydro. Solar, wind, modern biomass, geothermal, small hydro (below 10 MW) and ocean energy all together account for only 12% of total renewables. The new renewables account only for 2% of the world primary energy supply.

Biomass contributes about 12% of today's world primary energy supply, while in many developing countries, its contribution ranges from 40% to 50% [8].

World production of biomass is estimated at 146 billion metric tons a year, mostly wild plant growth. Some farm crops and trees can produce up to 20 metric tons per acre of biomass a year. Types of algae and grasses may produce 50 metric tons per year [1].

For its mission analysis study conducted for the US Department of Energy in 1979, Stanford Research Institute (SRI) chose five types of biomass materials to investigate for energy conversion: woody plants, herbaceous plants (those that do not produce persistent woody material), aquatic plants and manure. Herbaceous plants were divided into two categories, those with low moisture content and those with high moisture content [7].

5. Energy from biomass

Biomass is not in ideal form for fuel use. The heat content calculated on a dry mass basis must be corrected for the natural water content that can reduce the net heat available by as much as 20% in direct combustion applications. Gasification to low calorific gas carries an additional net energy loss, and conversion to synthetic natural gas and liquid fuels results in still greater reduction of net energy, to perhaps 30% of the original heat content [11].

Photosynthesis is a process by which plants use solar energy to transfer the low energy CO₂ into energy rich organic compounds. Thus, solar energy is captured and stored in the form of chemical energy.

Wood is still a predominant fuel in many non-OPEC, tropical, developing countries, and it will continue to be so for at least the next 40–50 years. It competes well with fossil fuels, because it is renewable, and with soft energies like solar and wind, on account of its energy storage capacity. It is being used in the domestic (for cooking and water heating), commercial (water heating) and industrial (for water heating and process heat) sectors and also in rural industries, like brick kilns, potteries etc.

Wood is a composite of cellulose, lignin and hemicellulose (43%, 36% and 22%, respectively). A typical analysis of dry wood yields carbon (52%), hydrogen (6.3%), oxygen (40.5%) and nitrogen (0.4%). The proximate analysis of wood shows the following components [7]:

- wood: volatile matter (80%), fixed carbon (19.4%) and ash (0.6%)
- bark: volatile matter (74.7%), fixed carbon (24%) and ash (1.3%).

The energy content of different plant materials determines their calorific value (heat content). This calorific value depends on the percentage of carbon and hydrogen, which are the main contributors to the heat energy value of a biomass material.

The characteristics of important fuelwoods indicate that the density of woods varies between 400 and 900 kg/m³, and the energy content (kcal/kg) varies between 4200 and 5400.

To get the maximum energy, the plant materials should be air dried because the amount of energy contained in the plant varies with the amount of moisture content. If the combustible materials are required for the energy recovery process, the amount of water in the plant material will affect the recoverable energy. The variations of calorific value of Indian firewoods indicate that with increasing moisture content, the calorific value decreases linearly [9]. Energy can be obtained from biomass in five ways:

- production of crops which yield starch, sugar, cellulose and oil
- solid waste which can be burnt
- anaerobic digestors which produce biogas which can be used to generate heat/electricity
- landfill production for methane
- biofuel production which includes ethanol, methanol, biodiesel and their derivatives.

Ethanol is blended with gasoline in the ratio of 1:9 to produce the fuel gasohol. Ethanol can also be used in fuel cells. The production of biodiesel has also gone up from 11,000 tons in 1991 to 1,286,000 tons in 1997. The raw materials are oils from 84% rapeseed, 13% sunflower, 1% soybean, 1% palm and 1% others [12].

Although wastes are still largely under utilized in some developed countries (such as Sweden) with a high land to population ratio and an active forest industry, their use is increasing rapidly, whilst costs (in real terms) drop significantly, resulting in as much as 15–18% contribution to national energy needs. Predictions suggest that in countries such as New Zealand, biomass mixed with hydro and wind could make the country completely reliant on renewables within the next 26 years, if the right financial support is given. Reports from the US, UK, Sweden, New Zealand and covering the EU indicate the efforts which are being made by governments to establish biomass as a long term resource within the framework of a sustainable, environmentally acceptable, cost effective policy linked to specific fiscal and legislative measures [7].

The cost of purposely grown biomass is still a major issue. The aims are to increase the use of residues whilst reducing costs (increasing yields) of biomass production, improve conversion efficiencies and improve economics (competitiveness with fossil fuels).

5.1. *Wood fuels*

Wood fuels are fuels derived from natural forests, natural woodlands and forestry plantations, namely fuelwood and charcoal from these sources. These fuels include sawdust and other residues from forestry and wood processing activities.

Fuelwood is the principal source for small scale industrial energy in rural areas of developing countries. Much of this fuelwood falls outside the commercial market, but increasingly; traded supplies are being used. Large reforestation programs will be required to meet future energy demands as the world population grows.

In industrialized countries, the predominant wood fuels used in the industrial sector are from wood processing industries. The utilization of this residue for energy production at or near its source has the advantage of avoiding expensive transport costs. Domestic wood fuels are sources principally from land clearing and logging residues.

5.2. Agricultural residues

Large quantities of agricultural plant residues are produced annually worldwide and are vastly under utilized. The most common agricultural residue is the rice husk, which makes up 25% of rice by mass. Other plant residues include sugar cane fiber (known as bagasse), coconut husks and shells, groundnut shell and straw. Included in agricultural residue is waste, such as animal manure (e.g. from cattle, chicken and pigs), which is used extensively in developing countries and, in some instances, in developed countries to produce heat or gas.

5.3. Energy crops

Energy crops are crops grown specially for the purpose of producing energy. These include short rotation plantations (or energy plantations), such as eucalyptus, willows and poplars, herbaceous crops, such as sorghum, sugarcane and artichokes, and vegetable oil bearing plants, such as soya beans, sunflowers, cotton and rapeseed. Plant oils are important, as they have a high energy density. The oil extraction technology and the agricultural techniques are simple, and the crops are very hardy.

5.4. Urban wastes

Urban wastes include MSW generated by household and commercial activities and liquid waste or sewage. Most MSW is currently disposed of in landfill sites. However, the disposal of this waste is a growing problem worldwide. Much of the waste could be used for energy production through incineration and other processes. Japan currently incinerates more than 80% of its MSW [6]. It is also possible to use the methane produced in landfill sites for energy production.

5.5. Refuse derived biomass fuel

Biomass fuel is an organic material produced by plants, animals or microorganisms that can be burned directly as a heat source or converted into a gaseous or liquid fuel.

Refuse derived fuel (RDF) is the combustible material in domestic or industrial refuse. It consists mainly of plant material but may also include some plastics. RDF may be used raw and unprocessed, partially processed or highly processed in the form of pellets. These burn more efficiently and with lower emissions.

Animal dung has long been a fuel for cooking and heating in poor countries. Poultry litter consists of droppings from egg laying birds kept in cages or a mixture of droppings and wood shavings where the birds are free roaming.

Straw from cereal crops and other crops, such as rapeseed, offers a continuing resource of biomass. A number of combustion methods are being investigated, such as slicing straw and mixing it with coal or compressing it into bales which are burned whole. Another promising biomass source is copied wood. This is wood harvested on a three to five year cycle from fast growing trees grown on waste land or diversified farmland. The harvested wood is chipped to burn more efficiently.

6. Benefits of biomass

Biomass is a renewable, potentially sustainable and relatively environmentally benign source of energy. If grown and utilized on a sustainable basis, biomass is carbon dioxide neutral. Thus, the substitution of fossil fuels for energy production with biomass will result in a net reduction in greenhouse gas emissions and the replacement of a non-renewable energy source. Many large power producers in industrialized countries are looking to biomass as a means of meeting greenhouse gas reduction targets.

The natural decomposition of biomass produces methane, which is about twenty times more active as a greenhouse gas than carbon dioxide [7]. There is, therefore, an additional greenhouse gas emission benefit in burning biogas, landfill gas and biomass residues to produce carbon dioxide.

Biomass fuels have negligible sulfur content and, therefore, do not contribute to sulfur dioxide emissions, which cause acid rain. The combustion of biomass produces less ash than coal combustion, and the ash produced can be used as a soil additive on farm targets.

The combustion of agricultural and forestry residues and MSW for energy production is an effective use of waste products that reduces the significant problem of waste disposal, particularly in municipal areas.

Biomass is a domestic resource, which is not subject to world price fluctuations or the supply uncertainties of imported fuels. In developing countries in particular, the use of liquid biofuels, such as biodiesel and ethanol, reduces the economic pressures of importing petroleum products.

Perennial energy crops (grasses and trees) have lower environmental impacts than conventional agricultural crops.

6.1. *Benefits of biomass energy*

Biomass provides a clean, renewable energy source that could dramatically improve our environment, economy and energy security. Biomass energy generates far less air emissions than fossil fuels, reduces the amount of waste sent to landfills and decreases our reliance on foreign oil. Biomass energy also creates thousands of jobs and helps revitalize rural communities.

6.2. *Environmental impacts of biomass energy*

As with all forms of energy production, biomass energy systems raise some environmental issues that must be addressed. In biomass energy projects, issues such as air pollution, impacts on

forests and impacts due to crop cultivation must be addressed on a case by case basis. Unlike other non-renewable forms of energy, biomass energy can be produced and consumed in a sustainable fashion, and there is no net contribution of carbon dioxide to global warming. One example is a closed loop system in which carbon dioxide will be taken up by new plant growth at the same rate that it is released by using the harvested biomass for fuel. Such bioenergy crops would make little or no net contribution to atmospheric carbon dioxide as a greenhouse gas. On the other hand, when fossil fuels are burned, carbon is released that has been stored underground for millions of years, making a net contribution to atmospheric greenhouse gases. Therefore, if managed carefully, biomass energy can have significant environmental advantages over the use of fossil fuels. An appropriate level of biomass energy use can have less environmental impacts than our current means of energy production.

6.3. Constraints to biomass use

In nature, biomass is not concentrated, and so, the use of naturally occurring biomass requires transportation, which increases the cost and reduces the net energy production. Biomass has a low bulk density, which makes transportation and handling difficult and costly. The key to overcoming this problem is locating the energy conversion process close to a concentrated source of biomass, such as a sawmill.

The incomplete combustion of fuelwood produces organic particulate matter, carbon monoxide and other organic gases. If high temperature combustion is used, oxides of nitrogen will be produced. The health impact of air pollution inside buildings is a significant problem in developing countries, where fuelwood is burnt inefficiently in open fires for domestic cooking and space heating.

There is the potential for widespread use of natural forests to cause deforestation and localized fuelwood scarcity with serious ecological and social ramifications. This is currently occurring in Nepal, parts of India and in sub-Saharan Africa. However, it is widely accepted now that the conversion of forestland into agricultural land and urban areas is also a major cause of deforestation. In addition, in many Asian countries, much of the woodfuel used for energy purposes comes from non-forest areas.

There is a potential conflict over the use of land and water resources for biomass energy and other uses, such as food production.

Some biomass applications are not fully competitive at this stage. In electricity production, for example, there is strong competition from new, highly efficient natural gas fired combined cycle plants. However, the economics of biomass energy production are improving, and the growing concern about greenhouse gas emissions is making biomass energy more attractive.

The production and processing of biomass can involve significant energy input, such as fuel for agricultural vehicles and fertilizers, resulting in a poor energy balance for the biomass application. Biomass processes need to minimize the use of energy intensive and fossil fuel based inputs and maximize waste and energy recovery.

There are often political and institutional constraints to biomass use, such as policies, taxes and subsidies that encourage the use of fossil fuels. Energy prices often do not reflect the environmental benefits of biomass and other renewable energy resources.

6.4. Industrial and home use

Wood related industries and homeowners consume the most biomass energy. The lumber, pulp and paper industries burn their own wood wastes in large furnaces and boilers to supply 60% of the energy needed to run the factories. In our homes, we burn wood in stoves and fireplaces to cook meals and warm our residences.

Biomass is burned by direct combustion to produce steam, the steam turns a turbine and the turbine drives a generator, producing electricity. Because of potential ash build-up (which fouls boilers, reduces efficiency and increases costs), only certain types of biomass materials are used for direct combustion.

Gasifiers are used to convert biomass into a combustible gas (biogas). The biogas is then used to drive a high efficiency, combined cycle gas turbine.

Heat is used to convert biomass chemically into a pyrolysis oil. The oil, which is easier to store and transport than solid biomass material, is then burned like petroleum to generate electricity. Pyrolysis also can convert biomass into phenol oil, a chemical used to make wood adhesives, molded plastics and foam insulation. Wood adhesives are used to glue together plywood and other composite wood products.

Cellulose suitable for polymer manufacture is expensive. Petrochemical polymer substitutes were cheaper to produce and rapidly won over markets opened by cellulosic plastic and fibers. Whether cellulose can win back those markets depends on finding an economical crop to grow as a cellulose resource and the ability of cellulosic polymer scientists to develop new properties that can be used to create new products. Pulpwood is the chief resource for cellulose production. Demand for wood by the paper industry has caused prices to increase. Some chemical manufacturers are looking at alternative crops.

Purity is essential to make quality cellulose polymers, like rayon. More efficient methods have been developed to separate pure cellulose from the lignocellulose complex in the raw biomass resource. One method, steam explosion, produces cellulose, a partial hydrolyzate (product made by the chemical action of water or an acid) of hemicellulose, and a low molecular weight lignin.

Cellulose can be converted into glucose by acid digestion. The glucose will oxidize to produce lactic acid. Once the biomass chemical industry can supply the raw materials, low cost lactic acid will compete as a direct substitute for petrochemicals and take advantage of its own unique properties. Lactic acid forms lactide, and lactide can form polymers. These lactide polymers make transparent films and strong fibers and are biodegradable. Research and development for lactide polymers will tailor new products to meet requirements for specific end uses in direct competition to petrochemical polymers.

More research needs to be done to develop new product potential for the low molecular weight (LMW) lignin. Unlike lignins currently on the market, it is soluble in common organic solvents, like ethanol and acetone, making structural transformation easier. Key intermediates made from LMW lignins should be low priced because much of the cost of generating them will be covered by the value of the pure cellulose and hemicelluloses produced during the steam explosion process. Phenol and benzene can be made from LMW lignin in direct substitution for petrochemical processes, or indirect substitutes may be made in the form of phenolics or epoxies [13].

Phenol formaldehyde (PF) resins represent a 1.2 billion pound/year market for phenol in the US [7]. Low purity phenols may be used for PF resins, since in their final form, PF resins are highly

cross linked and relatively insensitive to impurities. Ablative fast pyrolysis is used to convert solid biomass into a liquid pyrolysis oil in high yields while minimizing the formation of char and permanent gases. The liquid pyrolysis oil is then subjected to a solvent extraction process to recover the phenol rich phenolics neutrals (PN) fraction. Depending on the biomass feedstock, 18–20 wt.% of the original biomass may be recovered in the PN fraction. This PN fraction can then be formulated into PF resins that are useful as wood adhesives and injection molded plastics. Up to 50% of the phenol in a typical PF resin can be replaced with PN without a substantial decline in the physical properties of the wood adhesives or injection molded plastics. Biomass from a number sources, i.e hardwoods, softwoods, annual grasses and wood bark, have been evaluated as feedstocks for the production of PN. The source of the feedstock does have some impact on the quality of the resins or plastics. Softwoods and grasses appear to be attractive feedstocks.

6.5. The future of biomass

In the future, biomass has the potential to provide a cost effective and sustainable supply of energy, while at the same time, aiding countries in meeting their greenhouse gas reduction targets. By the year 2050, it is estimated that 90% of the world population will live in developing countries [6]. It is critical, therefore, that the biomass processes used in these countries are sustainable. The modernization of biomass technologies, leading to more efficient biomass production and conversion, is one possible direction for biomass use in developing countries.

In industrialized countries, the main biomass processes utilized in the future are expected to be direct combustion of residues and wastes for electricity generation, bio-ethanol and biodiesel as liquid fuels and combined heat and power production from energy crops. In the short to medium term, biomass waste and residues are expected to dominate biomass supply, to be substituted by energy crops in the longer term. The future of biomass electricity generation lies in biomass integrated gasification/gas turbine technology, which offers high energy conversion efficiencies.

Biomass will compete favorably with fossil mass for niches in the chemical feedstock industry. Biomass is a renewable, flexible and adaptable resource. Crops can be grown to satisfy changing end use needs. The success of the biomass derived chemicals industry will depend on the supply and demand for feedstock, primary chemicals and key intermediates the petrochemical industry cannot make, such as cellulose, lactic acid and levulinic acid. The first thermoplastics and synthetic fibers were made from cellulose derivatives. Acetaldehyde, a major petrochemical key intermediate, can be made from lactic acid. Levulinic acid salts have been proposed to replace ethylene glycol as an engine coolant.

7. Biomass conversion processes

Biomass conversion may be conducted on two broad pathways: chemical decomposition and biological digestion. The conversion technologies for utilizing biomass can be separated into four basic categories: direct combustion processes, thermochemical processes, biochemical processes and agrochemical processes.

Thermochemical decomposition can be utilized for energy conversion of all five categories of biomass materials, but low moisture herbaceous (small grain field residues) and woody (woody industry wastes and standing vegetation not suitable for lumber) are the most suitable. Biological

processes are essentially microbic digestion and fermentation. High moisture herbaceous plants (vegetables, sugar cane, sugar beet, corn, sorghum, cotton) marine crops and manure are most suitable for biological digestion.

Extraction is another, mainly mechanical, process for producing an energy carrier from biomass (e.g. rapeseed oil from rapeseed). With regard to the energy carriers produced from biomass, a distinction can be made between the production of heat, electricity and fuels. There are numerous ongoing technological developments in the field of biomass energy conversion. A detailed overview is, however, beyond the scope of this introduction. Such an overview can be found elsewhere, for example in a report by Van den Heuvel [14].

7.1. Direct combustion processes

Combustion is widely used on various scales to convert biomass energy to heat and/or electricity with the help of a steam cycle (stoves, boilers and power plants). Production of heat, power and (process) steam by means of combustion is applied for a wide variety of fuels and from very small scale (for domestic heating) up to a scale in the range of 100 MW_e. Co-combustion of biomass in (large and efficient) coal fired power plants is an especially attractive option as well because of the high conversion efficiency of these plants. It is a proven technology, although further improvements in performance are still possible. Net electrical efficiencies for biomass combustion power plants range from 20% to 40%. The higher efficiencies are obtained with systems over 100 MW_e or when the biomass is co-combusted in coal fired power plants [15].

Direct combustion is the main process adopted for utilizing biomass energy. The energy produced can be used to provide heat and/or steam for cooking, space heating and industrial processes, or for electricity generation.

Small scale applications, such as domestic cooking and space heating, can be very inefficient, with heat transfer losses of 30–90%. This problem can be addressed through the use of more efficient stove technology.

On a larger scale, biomass, such as fuelwood, forestry residues, bagasse and MSW, can be combusted in furnaces and boilers to produce process heat, or steam for a steam turbine generator. Power plant size is constrained by the local feedstock availability and is generally less than 25 MW. However, by using dedicated feedstock supplies, such as short rotation plantations or herbaceous energy crops, the size can be increased to 50–75 MW, gaining significant economics of scale [16]. In developing countries, power generation is usually required in smaller increments, and agricultural residues, such as rice husk and nutshells, can easily meet feedstock requirements.

Large biomass power generation systems can have comparable efficiencies to those of fossil fuel systems, but this comes at a higher cost due to the moisture content of biomass. However, by using the biomass in combined heat and electricity production systems (or cogeneration systems), the economics are significantly improved. Cogeneration is viable where there is a local demand for both heat and electricity.

7.2. Thermochemical conversion processes

Thermochemical conversion processes can be subdivided into gasification, pyrolysis, and direct liquefaction. The last two processes are sometimes confused with each other, and a simplified

Table 1

Comparison of liquefaction and pyrolysis

Process	Temperature	Pressure (MPa)	Drying
Liquefaction	525–600	5–20	Unnecessary
Pyrolysis	650–800	0.1–0.5	Necessary

comparison of the two follows. Both are thermochemical processes in which feedstock organic compounds are converted into liquid products. In the case of liquefaction, feedstock macromolecule compounds are decomposed into fragments of light molecules in the presence of a suitable catalyst. At the same time, these fragments, which are unstable and reactive, repolymerize into oily compounds having appropriate molecular weights. With pyrolysis, on the other hand, a catalyst is usually unnecessary, and the light decomposed fragments are converted to oily compounds through homogeneous reactions in the gas phase. The differences in operating conditions for liquefaction and pyrolysis are shown in Table 1.

7.2.1. Pyrolysis

Pyrolysis is the thermochemical process that converts biomass into liquid (bio-oil or bio-crude), charcoal and non-condensable gases, acetic acid, acetone and methanol by heating the biomass to about 750 K in the absence of air. The process can be adjusted to favor charcoal, pyrolytic oil, gas or methanol production with a 95.5% fuel-to-feed efficiency. Pyrolysis can be used for the production of bio-oil if flash pyrolysis processes are used, and it is currently at the pilot stage [17]. Pyrolysis produces energy fuels with high fuel-to-feed ratios, making it the most efficient process for biomass conversion and the method most capable of competing with and eventually replacing non-renewable fossil fuel resources. The conversion of biomass to crude oil can have an efficiency up to 70% for flash pyrolysis processes. The so-called bio-crude can be used in engines and turbines. Its use as feedstock for refineries is also being considered. Some problems in the conversion process and use of the oil need to be overcome. These include poor thermal stability and corrosivity of the oil. Upgrading by lowering the oxygen content and removing alkalis by means of hydrogenation and catalytic cracking of the oil may be required for certain applications [18].

Pyrolysis is the basic thermochemical process for converting biomass to a more useful fuel [19]. Biomass is heated in the absence of oxygen, or partially combusted in a limited oxygen supply, to produce a hydrocarbon rich gas mixture, an oil-like liquid and a carbon rich solid residue. Traditionally in developing countries, the solid residue produced is charcoal, which has a higher energy density than the original fuel and is smokeless and, thus, ideal for domestic use. The traditional kilns are simply mounds of wood covered with earth, or pits in the ground. However, the process of carbonization is very slow and inefficient in these kilns and more sophisticated kilns are replacing the traditional ones.

Chemical decomposition through pyrolysis is the same technology used to refine crude fossil fuel oil and coal. Biomass conversion by pyrolysis has many environmental and economic advantages over fossil fuels, but coal and oil production dominate because costs are kept lower by various means, including government protection.

Pyrolysis has been used since the dawn of civilization. If some means is applied to collect the off-gases (smoke), the process is called wood distillation. The ancient Egyptians practiced wood distillation by collecting tars and pyroligneous acid for use in their embalming industry. Pyrolysis of wood to produce charcoal was a major industry in the 1800s, supplying the fuel for the industrial revolution, until it was replaced by coal. In the late 19th century and early 20th century, wood distillation was still profitable for producing soluble tar, pitch, creosote oil, chemicals and non-condensable gases often used to heat boilers at the facility. The wood distillation industry declined in the 1930s due to the advent of the petrochemical industry and its lower priced products. However, pyrolysis of wood to produce charcoal for the charcoal briquette continued [20].

The wood distillation industry used pyrolytic reactors in a process called destructive distillation. The operation was performed in a fractionating column (a tall still) under high temperature (from 750 to 1350 K). Charcoal was the main fuel product, and methanol production was about 1–2% of volume, or 6 gallons per ton. This traditional method was replaced by the synthetic process developed in 1927 [7]. The synthetic process utilizes a pyrolytic reactor, operating as a gasifier by injecting air or pure oxygen into the reactor core to completely burn the biomass to ash. The energy contained in the biomass is released in the gases formed. After purification, the syngas, hydrogen and carbon monoxide in a 2 to 1 ratio, is altered by catalyst under high pressure and temperature to form methanol. This method will produce 100 gallons of methanol per ton of feed material [21].

Pyrolysis of wood has been studied as a zonal process with zone A (easily degrading zone) occurring at temperatures up to 473 K. The surface of the wood becomes dehydrated at this temperature, and along with water vapour, carbon dioxide, formic acid, acetic acid and glyoxal are given off. When temperatures of 473–533 K are attained, the wood is said to be in zone B and is evolving water vapor, carbon dioxide, formic acid, acetic acid glyoxal and some carbon monoxide. The reactions to this point are mostly endothermic, the products are largely non-condensable and the wood is becoming charred. Pyrolysis actually begins between 535 and 775 K, which is called zone C. The reactions are exothermic, and unless heat is dissipated, the temperature will rise rapidly. Combustible gases, such as carbon monoxide from cleaving of the carbonyl group, methane, formaldehyde, formic acid, acetic acid, methanol and hydrogen are being liberated and charcoal is being formed. The primary products are beginning to react with each other before they can escape the reaction zone [11]. If the temperature continues to rise above 775 K, a layer of charcoal will be formed that is the site of vigorous secondary reactions and is classified as zone D. Carbonization is said to be complete at temperatures of 675–875 K. The thermal degradation properties of hemicelluloses, celluloses and lignin can be summarized as follows [22]:

thermal degradation of hemicelluloses > of cellulose ≫ of lignin

If the purpose is to maximize the yield of liquid products resulting from biomass pyrolysis, a low temperature, high heating rate, short gas residence time process would be required. For high char production, a low temperature, low heating rate process would be chosen. If the purpose is to maximize the yield of fuel gas resulting from pyrolysis, a high temperature, low heating rate, long gas residence time process would be preferred.

Table 2

Results of pyrolysis of solid waste and analysis of the gas content

Temperature (K)	Char (wt.%)	Liquid (wt.%)	Gas (wt.%)	CO ₂ (vol%)	O ₂ (vol%)	HC (vol%)	CO (vol%)	Others (vol%)
507	97.0	0.0	3.0	22.1	0.6	32.5	13.8	31.0
584	76.2	15.9	7.9	18.9	3.9	32.9	18.2	26.1
655	62.9	25.4	11.7	34.5	0.4	21.4	10.6	33.1
683	49.0	35.0	16.0	45.1	4.6	20.9	9.4	19.7

Solid waste of a city (Istanbul, Turkey) was pyrolysed in a nitrogenous ambient pressure at different temperatures. The results from the solid waste of the city are given in Table 2.

A wide spectrum of organic substances, contained in the pyrolytic liquid fractions, is given in Table 3 [23]. The liquid fraction of the pyrolysis products consists of two phases: an aqueous phase containing a wide variety of organo-oxygen compounds of LMW and a non-aqueous phase containing insoluble organics (mainly aromatics) of high molecular weight [24]. This phase is called as bio-oil or tar and is the product of greatest interest. The ratios of acetic acid, methanol, and acetone of aqueous phase were higher than those of non-aqueous phase [24]. The characterization of the chemistry and products from pyrolysis of lignocellulosic materials are given in Table 4.

7.2.2. Gasification

Gasification is a form of pyrolysis, which is performed at high temperatures in order to optimize gas production. The resulting gas, known as producer gas, is a mixture of carbon monoxide, hydrogen and methane, together with carbon dioxide and nitrogen. The gas is more versatile than the original solid biomass (usually wood or charcoal). It can be burnt to produce process heat and steam, or used in gas turbines to produce electricity.

Biomass gasification is the latest generation of biomass energy conversion processes, and is being used to improve the efficiency and to reduce the investment costs of biomass electricity generation through the use of gas turbine technology. High efficiencies (up to about 50%) are achievable using combined cycle gas turbine systems, where waste gases from the gas turbine are recovered to produce steam for use in a steam turbine. Economic studies show that biomass gasification plants can be as economical as conventional coal fired plants [25].

Commercial gasifiers are available in a range of sizes and types and run on a variety of fuels, including wood, charcoal, coconut shells and rice husks. Power output is determined by the economic supply of biomass, which is limited to 80 MW in most regions [16].

7.2.3. Supercritical fluid extraction

Conversion by supercritical fluid extraction of biomass to liquids has been demonstrated with the use of a number of processing configurations [26–28]. These different processing techniques tend to emphasize different mechanism subsets within the large group of potential chemical mechanisms by which biomass is converted to primary products and thereafter further converted by varying degrees to final products.

Table 3

Chemical analysis of organic substances contained in the fractions of liquid pyrolysis products from deciduous woods at 725 K (wt.% dry basis)

Substance	
Acetic acid	16.78
1-hydroxy-2-propanone	7.01
Methanol	4.11
1-hydroxy-2-butanone	3.47
Furfural	2.09
2,6-dimethoxyphenol	1.97
Levoglucosan	1.89
α -angelilactone	1.81
4-methyl-2,6-dimethoxyphenol	1.81
1-hydroxy-2-propane acetate	0.86
Guaiaicol	0.82
1-hydroxy-2-butanone acetate	0.67
Crotonic acid	0.66
Formic acid	0.66
Butyrolactone	0.66
Crotonic acid	0.66
Propionic acid	0.59
Ethanal	0.54
2,3-butanedione	0.54
2,3-pentanedione	0.54
Valeric acid	0.54
Isovaleric acid	0.54
5-methyl-furfural	0.33
Valerolactone	0.33
Butyric acid	0.33
Isobutyric acid	0.33
Propanone	0.33
Acrylic acid	0.33
2-butanone	0.33
Methyl acetate	0.21
Methyl-furyl-acetone	0.16
Crotonolactone	0.16
2-methyl-cyclopentenone	0.16
Cyclopentenone	0.16

7.2.4. Liquefaction

Liquefaction is a low temperature, high pressure thermochemical process using a catalyst. The process produces a marketable liquid product. Liquefaction takes place at moderate temperatures at high pressure with the addition of hydrogen. The interest in liquefaction is low because the reactors and fuel feeding systems are more complex and more expensive than for pyrolysis processes [17].

Concerning the catalytic effect of alkali hydroxides and carbonates, there has been little description about the roles that a catalyst plays in liquefaction with some exceptions. Appell et al.

Table 4

Characterization of chemistry and products of biomass pyrolysis

Type	Feature and process	Products and their characterizations
Pyrolysis of holocellulose	<i>General effects</i> Color changes from to brown to black Flexibility and mechanical strength are lost Size reduced Weight reduced	<i>Volatile products</i> Readily escape during pyrolysis process 59 compounds produced of which 37 have been identified CO, CO ₂ , H ₂ O, acetal, furfural, aldehydes, ketones
	<i>Processes</i> Dehydration Also known as char forming reactions Produces volatiles products and char Depolymerization Produces tar Effect of temperature At low temperatures dehydration predominates At 630 K depolymerization with production of levoglucosan dominates Between 550 and 675 K products formed are independent of temperature	<i>Tar</i> Levoglucosan is principal component <i>Chars</i> As heating continues there is a 80% loss of weight and remaining cellulose is converted to char Prolonged heating or exposure to higher temperature (900 K) reduces char formation to 9%
Pyrolysis of lignin	<i>Conventional (carbonization)</i> At 375–450 K endotherm At 675 K exotherm Maximum rate occurring between 625 and 725 K	<i>Char</i> Approximately 55% <i>Distillates (20%)</i> Methanol–methoxyl groups, acetic acid Acetone <i>Tar (15%)</i> Phenolic compounds and carboxylic acid <i>Gases</i> CO, methane, CO ₂ , ethane
	<i>Fast and flash pyrolysis</i> High temperature of 750 K Rapid heating rate Finely ground feed material Less than 10% MC Rapid cooling and condensation of gases Yields in 80% range Char and gas used for fuel	<i>Bio-oil</i> Will not mix with hydrocarbon liquids Cannot be distilled Substitute for fuel oil and diesel in boilers, furnaces, engines, turbines etc. <i>Phenols</i> Utilizes a solvent extraction process to recover phenolics and neutrals 18–20% of wood wt. Secondary processing of phenol formaldehyde resins Adhesives Injected molded plastics <i>Other chemicals</i> Extraction process Chemical for stabilizing the brightness regression of thermochemical pulp (TMP) when exposed to light Food flavorings, resins, fertilizers, etc.

proposed the mechanism for sodium carbonate catalyzed liquefaction of carbohydrate in the presence of carbon monoxide [29].

7.2.5. Hydro thermal upgrading process

Another way to produce bio-crudes is the hydro thermal upgrading (HTU) process. HTU converts biomass in a wet environment at high pressure to partly oxygenated hydrocarbons. The process is almost at the pilot stage [30].

7.3. Biochemical processes

7.3.1. Anaerobic digestion

Anaerobic digestion is the decomposition of biomass through bacterial action in the absence of oxygen. It is essentially a fermentation process and produces a mixed gas output of methane and carbon dioxide. The product generated by the decay, in the absence of air, of sewage or animal waste is known as biogas. The anaerobic digestion of MSW buried in landfill sites produces a gas known as landfill gas.

Biogas is most commonly produced by using animal manure mixed with water which is stirred and warmed inside an airtight container, known as a digester. Digesters range in size from around 1 m³ for a small household unit to as large as 2000 m³ for a large commercial installation [6]. The biogas produced can be burnt directly for cooking and space heating, or used as fuel in internal combustion engines to generate electricity.

The methane gas produced in landfill sites eventually escapes into the atmosphere. However, the landfill gas can be extracted from existing landfill sites by inserting perforated pipes into the landfill. In this way, the gas will travel through the pipes under natural pressure for use as an energy source, rather than simply escaping into the atmosphere to contribute to greenhouse gas emissions.

Alternatively, new landfill sites can be specially developed in a configuration which encourages anaerobic digestion. In these new sites, the pipe system for gas collection is laid down before the waste is deposited, thus optimizing the gas output, which can be as high as 1000 m³/h. The landfill gas is generally used for electricity generation, using large internal combustion engines. Typically, the engines drive 500 kW generators to match the normal gas supply rates of around 10 GJ/h. One of the largest landfill gas plants in the world is a 46 MW plant in California [6].

7.3.2. Alcoholic fermentation

Ethanol can be produced from certain biomass materials which contain sugars, starch or cellulose. The best known source of ethanol is sugar cane, but other materials can be used, including wheat and other cereals, sugar beet, jerusalem artichoke and wood. The choice of biomass is important as feedstock costs typically make up 55–80 % of the final alcohol selling price [3]. Starch based biomass is usually cheaper than sugar based materials but requires additional processing. Similarly, cellulose materials, such as wood and straw, are readily available but require expensive preparation.

Ethanol is produced by a process known as fermentation. Typically, sugar is extracted from the biomass crop by crushing, mixed with water and yeast and kept warm in large tanks called fermenters. The yeast breaks down the sugar and converts it to methanol. A distillation process is required to remove the water and other impurities in the diluted alcohol product (10–15% ethanol). The concentrated ethanol (95% by volume with a single step distillation process) is drawn off and condensed to a liquid form.

Ethanol can be used as a supplement or substitute for petrol in cars. Brazil has a successful industrial scale ethanol project which produces ethanol from sugar cane for blending with petrol. Some vehicle adaptations are required for full petrol substitution.

Crop residues are often used to supply the external heat required for the process. There is a significant energy loss in the distillation stage, particularly the complex secondary distillation process required to achieve ethanol concentrations of 99% or better. This may be acceptable, however, due to the convenience of the liquid fuel and relatively low cost and maturity of the technology.

7.4. Agrochemical processes

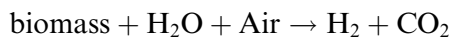
Seed crops, which contain a high proportion of oil, can be crushed and the oils extracted and used directly to replace Diesel (called biodiesel) or as a heating oil. The energy content of vegetable oils are 39.3–40.6 MJ/kg [31]. There are a wide range of crops that can be used for biodiesel production, but the most common crop is rapeseed. Other raw materials used are palm oil, sunflower oil, soya bean oil and recycled frying oils. The cost of the raw material is the most important factor affecting the overall cost of production. There are currently 85 biodiesel plants around the world (including one in Malaysia using palm oil) with a combined capacity of over 1.28 million tons [32]. In the Philippines, Diesel is blended with coconut oil and used in tractors and lorries.

There are a number of benefits associated with biodiesel, including a reduction in greenhouse gases of at least 3.2 kg of carbon dioxide-equivalent per kilogram of biodiesel, a 99% reduction of sulfur oxide emissions, a 39% reduction in particulate matter, a high biodegradability and energy supply security [32].

7.5. Hydrogen from biomass

Hydrogen is a clean burning fuel. It is not a primary fuel it must be manufactured from water with either fossil or non-fossil energy sources. Hydrogen is produced from pyrolygneous oils produced from the pyrolysis of lignocellulosic biomass [33].

Gasification of solid wastes and sewage is a recent innovation. The synthesis gas formed with air or oxygen is reformed to hydrogen. The solid waste concept solves two problems: (1) disposal of urban refuse and sewage and (2) a source of hydrogen fuel for hydrogen powered vehicles [34]. Hydrogen from biomass has generally been based on the following reactions [35]:



8. Conclusion

Biomass conversion may be conducted on two broad pathways: chemical decomposition and biological digestion. Thermochemical conversion processes can be subdivided into gasification,

pyrolysis and direct liquefaction. At present, the conversion of logs into sawed wood and veneer gives rise to considerable volumes of residues. Successful commercial ways of utilizing these include particleboard, hardboard, fibreboard and pulp. In addition, the chemistry of wood offers some potential. Both softwoods and hardwoods contain cellulose, lignin, hemicellulose and chemical extractives. Liquefaction is a low temperature, high pressure thermochemical process using a catalyst. The process produces a marketable liquid product. Through the process called hydrolysis, these wood elements can be converted into wood sugars and alcohols for use in the chemical industry, but in practice, it is difficult to do this in competition with cheaper petrochemicals. Rayon can be produced from wood. There is also the process of pyrolysis, which is the destructive distillation of wood. It is a process which has been known from ancient times. It produces, in the first instance, charcoal, but other by-products arise, including methanol, acetone, acetic acid and tars. Again, success in commercial terms depends on the ability to compete with petrochemicals. Non-timber products from trees may, at present, be more cheaply produced from other materials, but the fact that these prospects exist further underlines the extraordinary number of ways in which they can serve the human race.

References

- [1] Cuff DJ, Young WJ. US energy atlas. New York: Free Press/McMillan; 1980.
- [2] Twidell J. Biomass energy. *Renew Energy World* 1998;3:38–9.
- [3] World Energy Council 1994. New renewable energy resources. Kogan Page, London, 1994.
- [4] Demirbaş A. Fuel properties and calculation of higher heating values of vegetable oils. *Fuel* 1998;77:117–1120.
- [5] Demirbaş A. Determination of combustion heat of fuels by using non-calorimetric experimental data. *Energy Edu Sci Technol* 1998;1:7–12.
- [6] Ramage J, Scurlock J. Biomass. Renewable energy-power for a sustainable future. In: Boyle G, editor. Oxford: Oxford University Press; 1996.
- [7] Demirbaş A. Biomass resources for energy and chemical industry. *Energy Edu Sci Technol* 2000;5:21–45.
- [8] Garg HP, Datta G. Global Status on Renewable Energy. International Workshop, Iran University of Science and Technology. 19–20 May 1998.
- [9] Reddy BS. Biomass energy for India: an overview. *Energy Convers Mgmt* 1994;35:341–61.
- [10] Kaygusuz K. Rural energy resources: applications and consumption in Turkey. *Energy Sourc* 1996;19:549–57.
- [11] Goldstein IS. Organic chemical from biomass. Boca Raton, Florida, USA: CRC Press; 1981. p. 64.
- [12] Jain RK, Singh B. Fuelwood characteristics of selected indigenous tree species from central India. *Bioresource Technol* 1999;68:305–8.
- [13] Parkhurst Jr HJ, Huibers DTA, Jones MW. Production of phenol from lignin. *ACS Div Pet Chem* 1980;25:657–67.
- [14] Van den HE. Energy conversion routes for biomass. Biomass Technology Group, University of Twente, Enschede, 1994.
- [15] Broek R, Faaij A, Wijk A. Biomass combustion power generation technologies. *Biomass Bioenergy* 1996;11:271–81.
- [16] Overend RP. Biomass gasification: a growing business. *Renew Energy World* 1998;1:59–63.
- [17] EUREC Agency. The future for renewable energy, prospects and directions. London: James and James Science Publishers; 1996.
- [18] Demirbaş A, Güllü D. Acetic acid, methanol and acetone from lignocellulosics by pyrolysis. *Energy Edu Sci Technol* 1998;2:111–5.
- [19] Demirbaş A. Yields of oil products from thermochemical biomass conversion processes. *Energy Convers Mgmt* 1998;39:685–90.
- [20] Demirbaş A. Properties of charcoal derived from hazelnut shell and the production of briquettes using pyrolytic oil. *Energy* 1999;29:141–50.

- [21] Rowell RM, Hokanson AE. Methanol from wood: a critical assessment, in progress. In: Sarkanen KV, Tillman DA, editors. Biomass conversion, vol. 1. New York: Academic Press; 1979.
- [22] Chum HL. Polymers from biobased materials. New Jersey, USA: Noyes Data Corporation; 1991.
- [23] Beaumont O. Flash pyrolysis products from beech wood. *Wood Fiber Sci* 1985;17:228–39.
- [24] Wenzl HFJ, editor. Further destructive processing of wood. The chemical technology of wood. New York: Academic Press; 1970 [chapter 5].
- [25] Badin J, Kirschner J. Biomass greens US power production. *Renew Energy World* 1998;1:40–5.
- [26] Küçük MM, Tunç M. Supercritical fluid extraction of biomass. *Energy Edu Sci Technol* 1999;2:1–5.
- [27] Demirbaş A, Tüzen M, Özdemir M. Supercritical fluid extraction of phenolic acids in snowdrop. *Energy Edu Sci Technol* 1999;2:47–52.
- [28] Akdeniz F, Küçük MM, Demirbaş A. Liquids from olive husk by using supercritical fluid extraction and thermochemical methods. *Energy Edu Sci Technol* 1998;1:17–22.
- [29] Appell HR, Fu YC, Friedman S, Yavorsky PM, Wender I. Report of Investigation 7560. US Bureau of Mines, Pittsburgh. 1971.
- [30] Goudriaan F, Naber JE, Louter AS. Production of crude oil from biomass. Biofuel vof, Heemskerk and Stork Comprimo BV. *Energy-en Milieuspectrum* 1/2, 1997 [in Dutch].
- [31] Demirbaş A. Calculation of higher heating values of biomass fuels. *Fuel* 1998;76:431–4.
- [32] Korbitz WE. From the field to the fast lane-biodiesel. *Renew Energy World* 1998;1:32–7.
- [33] Demirbaş A, Çağlar A. Catalytic steam reforming of biomass and heavy oil residues to hydrogen. *Energy Edu Sci Technol* 1998;1:45–52.
- [34] Veziroğlu T. Hydrogen energy, part A. New York: Plenum; 1975.
- [35] Demirbaş A, Karslıoğlu S, Ayas A. Hydrogen resources: conversion of black liquor to hydrogen rich gaseous products. *Fuel Sci Technol Int* 1996;14:451–63.