# Biomass energy and densification: A Global Review with Emphasis on Developing Countries

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## ABSTRACT

Biomass is the fourth largest source of energy worldwide and provides basic energy requirements for cooking and heating of rural households in developing countries. In developed countries, biomass energy use is mainly for space heating and power generation. In most developing countries, the share of traditional fuels in the total national energy use has been falling in recent years. This is mainly due to rather rapid growth in commercial energy consumption in these countries; however, the magnitude of biomass energy consumption in most of these countries has been actually rising. The share of biomass in the total energy consumption has been rising in developed countries in recent years.

A number of modern biomass energy technologies (BETs) are currently at different stages of research, development, demonstration and commercialization. The biggest improved cookstove programs of the world are being undertaken in China and India. Electricity generation based on biomass combustion employing boiler-steam turbine systems is well established. The current global installed capacity of electricity generation from biomass is about 40,000 MW. It is expected that power generation from biomass will substantially in the future. Co-firing of biomass with coal has been extensively demonstrated in several utility plants and appears to be an important option for utilizing biomass efficiently in the short term. The Whole Tree Energy (WTE) system is a special type of wood-fired system, in which whole tree trunks are combusted; the first WTE power plant of the world is expected to start up in mid-2004 in Minnesota, USA.

Fixed-bed gasification technology is more than a century old. Currently, interest in the fixed-bed biomass gasifier-engine system as an option for decentralized electricity generation is growing again, particularly in developing countries. Biomass integrated gasification combined cycle (BIGCC) plants are currently at an early stage of commercialization. The first plant was established at Varnamo in Sweden in 1995; several other BIGCC plants are in different stages of construction in the USA and Europe.

Ethanol can substitute gasoline in automotive engines. The world ethanol production in 1998 was 31.2 billion litres; the major producers of ethanol are Brazil and USA where production in 1998 was 13.5 and 6.4 billion litres respectively. Fuel ethanol accounts for about two-thirds of the total production.

Densification has aroused a great deal of interest in recent years as a technique of beneficiation of residues for utilization as energy source. Densified biomass produced is mostly in the form of briquettes in developing countries and in the form of pellets in developed countries.

Heated-die screw-press briquetting machines are almost exclusively used in the Asian countries east of India. In some of these countries, e.g. Malaysia, Philippines, and Thailand, biomass briquettes are mostly carbonized to obtain briquetted charcoal. In India, Africa and Latin America, piston presses are most commonly used for biomass densification, although a significant number of screw presses are also used in India. In Africa, large-scale briquetting plants have been established in Ethiopia, Kenya, Malawi, Uganda, Sudan, Zambia and Zimbabwe. Biomass briquettes have found limited application in certain other countries as well, e.g. Cameroon, Eritrea, Ghana, Rwanda, Senegal, Tanzania etc. In Latin America, densification is best established in Brazil, which, with an annual production of about 1 million tons, appears to be biggest producer of densified biomass in the world; it appears that densification is not common in the other countries of the region.

Growing global concerns regarding climate change and related developments are likely to improve the prospects of biomass energy technologies, including densification in the near future.

# I. INTRODUCTION

Global primary commercial energy consumption has grown at an average annual rate of about 2% per year over the last two hundred years; during 1990-2000, the consumption increased by 11%. Currently, conventional commercial energy sources - coal, oil, natural gas, nuclear and hydropower - account for 85-90% of global primary energy consumption; fossil fuels account for approximately ninety per cent of the conventional commercial energy consumption.

Since developing countries are at initial stages of industrialization, their energy consumption has been growing at greater rates compared with developed countries. Thus, during 1990-2000, conventional energy consumption of the developing countries of the Asia Pacific region increased by 27 per cent compared with 11 per cent growth of the world consumption.

The trend of growth in global energy consumption is expected to continue in the future - primarily because of the expected growth in world population and the expected economic growth of the developing countries. It is likely that the current pattern of energy consumption, which is characterized by continued growth and heavy dependence on fossil fuels, cannot be sustained in the future because of two major constraints. One of these is the environmental impact of using fossil fuels, particularly climate change and the other is the depletion of the reserves of fossil fuels. Since the biggest source of greenhouse gas (GHG) emission is the combustion of fossil fuels, one of the most effective approaches to the mitigation of GHG emission would be reducing consumption of these fuels through their substitution by renewable energy. The same approach is also vital for reducing the rate of depletion of fossil fuels, particularly oil, the proved reserve of which at the end of 2000 was about 40 years of consumption at the prevailing level.

Biomass is the fourth largest source of energy worldwide and provides basic energy requirements for cooking and heating of rural households in developing countries. Use of biomass fuels is also well established in certain commercial establishments and industries. In developed countries, biomass energy use in developed countries is mainly for space heating and power generation. The biomass fuels could potentially provide a much more extensive energy service than at present if these were used efficiently. Besides efficiency improvements of existing energy systems, putting huge quantities of biomass, mostly in the form of agricultural residues and wastes, which are currently disposed by burning or dumping, could potentially increase the energy supply from biomass substantially. Significant additional increase in biomass energy supplies should be possible through energy plantation.

Utilization of biomass residues and wastes is often difficult due to their uneven and troublesome characteristics. This drawback can be overcome by means of densification, i.e. compaction of the residues into products of high density and regular shape. Densification has aroused a great deal of interest worldwide in recent years as a technique of beneficiation of residues for utilization as energy source.

This paper consists of two sections - a global review of biomass energy in general and a review of the current status of biomass densification, with particular emphasis on developing countries.

# II. BIOMASS ENERGY TECHNOLOGIES

In developing countries, energy required for cooking often constitutes the biggest share of the total national energy consumption and is normally met mostly by biomass. Traditional biomass fired cooking stoves have two major drawbacks, i.e., low efficiency and indoor air pollution created by pollutants (which have been linked to different health problems) released inside the kitchen. The biggest improved cookstove (ICS) programs of the world are being undertaken in China where 177 million stoves have been installed so far covering 76 percent of rural households (Junfeng et al. 2000) and in India where about 33.8 million improved stoves were installed by 2001 (MNES, 2002). Although a large number of improved wood-fired cooking stoves have been developed in different countries, most of these basically aim to overcome the two major drawbacks of traditional stoves as pointed out above. Modern wood fired cooking facilities, besides addressing these drawbacks, have to provide convenience similar to those available with kerosene or gas based cooking, e.g. easy control of heat release rate, easy and quick start-up/shut down etc. Currently, such biomass based modern cooking systems are not yet commercially available but appear to be in early stages of development.

A number of technologies exist for large-scale combustion of biomass. Electricity generation based on biomass combustion employing boiler-steam turbine systems is well established in situations where relatively cheap/waste biomass is available. The current global installed capacity of electricity generation from biomass is about 40,000 MW (Turkenburg, 2000). There is a growing interest in electricity generation from biomass worldwide; thus, in Asia it is projected that by 2015, China will have between 3,500 and 4,100 MW of biomass based capacity and India will have 1,400-1,700 MW.

Biomass based cogeneration technology is well established in the pulp and paper industry, plywood industry as well as a number of agro-industries, for example, sugar mills and palm oil mills. Normally, there is substantial scope for efficiency improvements in such cases. India has launched the world's largest sugar-mill based cogeneration program; a capacity of 358 MW has so far been commissioned and 389 MW is under installation. In Brazil, the world's largest sugar cane producer, the surplus power generation in sugar industry in 1999 was only about 40 MW while the full potential of condensing extracting steam turbine based cogeneration is estimated to be about 9000 MW (Walter, 2002); however, the industry appears to ready for investments in modern cogeneration.

Co-firing biomass with coal (with only a part of the total energy coming from biomass) in existing coal-fired plants appears to be an important option for utilizing biomass efficiently in the short term. A number of cofiring commercial utility plants are in operation in developed countries, particularly the USA. Experience so far shows that effective substitution of coal by biomass can be made up to about 15 per cent of the total energy input with little more than burner and feed intake system modifications to existing pulverized coal units.

Fixed bed gasification technology is more than a century old. During World War II, more than one million gasifiers were in use for operating trucks, buses, taxis, boats, trains etc. in different parts of the world. Interest in fixed bed biomass gasifier-engine systems as an option for decentralized electricity generation is growing again, notably in India, and China, where fixed bed gasifiers are commercially available. In India, 1756 gasifier systems with a total capacity of 42.82 MW (equilavent) were installed by the end of 2001. An interesting new development in thermal application of producer gas is its use for cooking. Networks of producer gas supply have been reported to exist in Shandong and Hubei provinces of China. The gasifiers use agricultural and forest residues and one gasifier set can supply about 100 households with gas for heating and cooking. Gasifiers have also been demonstrated/used in several countries around the world, e.g. Brazil, Indonesia, Philippines, Thailand and Sri Lanka.

Biomass integrated gasification combined cycle (BIGCC) plants are currently at an early stage of commercialization. The first plant was established at Varnamo in Sweden in 1995. At present, several BIGCC plants, of capacities up to 75 MW, are in different stages of implementation in the USA and Europe. Two BIGCC projects have been initiated in Brazil; one of these is based on eucalyptus wood, while the other is based on sugarcane bagasse and trash. In India, a BIGCC project is being initiated currently.

Biogas production from animal wastes is well established in China and India. In China, there were about 6.8 million household digesters and more than 1000 medium- and large-scale biogas plants for treatment of distillery and animal wastes by the end of 1997. In India, the number of household biogas digesters installed by 2001 has been estimated to be 3.275 million (MNES, 2002).

One of the most impressive renewable energy initiatives undertaken in the world so far is the ethanol programme in Brazil. With ethanol production of 11.4 billion litres in the year 2000, it is the largest ethanol producer of the world; the USA is the second largest producer. China has initiated a corn-to-ethanol project that will produce 600,000 tons of alcohol fuel annually when completed in 2003; the total capacity of this and other projects announced so far is 1.6 million tons per year. In Thailand, the government appears to be planning to establish a total production capacity of 2 million litres per day (Berg, 2001). The Indian government is setting up pilot projects to study the use of ethanol as transport fuel. Initially a blend of 5 per cent alcohol derived from sugarcane molasses and 95 per cent gasoline will be tried.

Biodiesel is a substitute for fossil diesel and can be used for running compression ignition engines. Although use of biodiesel is not yet common, it has been extensively tested by government agencies, university researchers and private industry in the United States and Europe. Europe, where the current annual production is 850,000 tonnes, is the leader in biodiesel utilization; USA with about 50,000 tonnes per year is the second largest producer. No significant biodiesel program exists in developing countries so far, although research on using biodiesel for running engines is in progress in a number of other countries, e.g. Malaysia, India, Nepal, Thailand etc. Also, Malaysia appears to be planning a 500,000 tonnes/year biodiesel plant.

The Whole Tree Energy (WTE) system is a special type of wood fired system, in which whole tree trunks, cut to about 25 ft long pieces, are utilized in the process of power generation in an innovative system that uses an integral fuel drying process. Flue gas is used to dry the wood stacked for about 30 days before it is conveyed to a boiler and burnt. Allowing the waste heat to dry the wet whole tree results in efficiency improvements, with net plant efficiency reaching comparable value of modern coal fired plants. The first WTE power plant of the world is expected to start up in mid-2004 in Minnesota, USA.

A Stirling engine is an external combustion engine; working on the principle of the Stirling thermodynamic cycle, the engine can be used to convert external heat from any suitable source, e.g. solar energy or combustion of fuels (biomass, coal, natural gas etc.) into power. Stirling engines can also be used for cogeneration by utilizing the rejected heat for space or water heating, or absorption cooling. A number of research institutes and manufacturers are currently engaged in developing biomass fired Stirling engine systems. At least one manufacturer offers waste heat powered Stirling engines commercially.

## III. STATUS OF BIOMASS ENERGY: COST, UTILIZATION AND PROSPECTS

### A. Cost

1. Cost of biomass fuels

Financial viability of biomass energy technologies largely depends on the cost of biomass fuels. However, the cost of biomass fuels strongly depends on the location/country as well as type. For example, a residue like rice husk may have a cost ranging from negative values in some situations, where it has to be disposed at a cost, to 10-20 US$ per ton in places where it is used for energy, or other purposes. Similarly, the cost of plantation grown biomass also varies quite widely (see Table 1). Thus, it is not possible to obtain any set of cost values of biomass fuels that would be globally applicable.

Table 2 shows the costs of a number of biomass and fossil fuels in the state of Iowa of USA (Brown et al., 2000). Although the cost values of Table 2 are for Iowa, the table provides an interesting comparison between various biomass and fossil fuels; also, the comparison is qualitatively valid in many situations at present. For example, for heat and power applications, plantation grown biomass cannot compete with coal, although agricultural residues (as represented by corn stalks in Table 2) can be delivered at a lower cost. Similarly, transportation fuels from biomass cannot compete with fuels derived from petroleum currently.

2. Cost of energy from biomass

Cost of final energy from biomass energy systems depends on costs associated with the fuel, e.g. plantation, harvesting, transportation etc. and costs associated with the energy systems, e.g., capital and maintenance costs.

a) Small-scale energy systems

Cost of energy for traditional thermal applications, for example cooking, varies quite widely. In most cases in rural areas, people collect their own biomass fuel and build their own stoves. Energy from biomass in such cases is practically free (if we neglect the value of the time for fuel collection and stove building). However, in situations where biomass fuels are purchased and utilized with low efficiency (say, about 10 per cent), the cost of useful energy delivered to the cooking pot may be substantial and even exceed cost of energy from LPG or kerosene, particularly if the fossil fuels are subsidized. Similar conclusions were drawn by Gupta and Ravindranath (1997), who assessed different cooking energy options for the case of India. The fuels considered were fuelwood, kerosene, biogas, liquefied petroleum gas (LPG), and electricity. They found that, for rural areas, an efficient/improved wood stove (Astra-stove) was the least cost option, and biogas was the most expensive option. The subsidized kerosene option was found to be cheaper than wood in the traditional stove. In the urban situation, the subsidy on kerosene makes it a low-cost fuel option, and fuelwood in the traditional stove is among the most expensive options.

For small-scale electricity generation, biomass energy may be more cost-effective compared with fossil fuel based generation under some situations. Thus, a number of studies show that gasifier based power generation in remote locations can be cheaper compared with diesel based power generation. This is further borne out by the growing number of remote power gasifier units in India.

Table 1. Summary of the Costs and Productivity of Plantation-grown Fuel

| Country | Delivered feedstock costs (US $/GJ) | Average productivity (dry tonnes/ha/yr) |
|---|---|---|
| United States (mainland) | $1.90 - $2.80 | 10 - 15.5 |
| Hawaii | $2.06 - $3.20 | 18.6 - 22.4 |
| Portugal | $2.30 | 15.0 |
| Sweden | $4.00 | 6.5 - 12.0 |
| Brazil (Northeast) | $0.97 - $4.60 | 3.0 - 21.0 |
| China (Southwest) | $0.60 | 8.0 |
| Philippines | $0.42 - $1.18 | 15.4 |

*Source: http://bioenergy.ornl.gov/reports/fuelwood/chap5.html*

Table 2. Estimated Costs of Biomass Fuels in Iowa, USA

| Fuel | Cost, US$/GJ |
|---|---|
| **Transportation** | |
| Diesel | 4.84 |
| Gasoline | 5.31 |
| Methanol from natural gas | 15.30 |
| Biodiesel | 10.72-21.16 |
| Ethanol from cellulose | 18.21 |
| Ethanol from corn | 11.86-26.47 |
| Methanol from Biomass | 14.61-31.50 |
| **Heat and Power** | |
| Corn stalks | 0.47 |
| Sub-bituminous coal | 0.95 |
| Natural gas | 1.90-4.74 |
| Hybrid poplar | 2.28-2.85 |
| Switchgrass | 2.75-3.32 |
| LPG | 4.65-8.06 |

*Source: Brown et al. (2001)*

b) Large-scale energy systems

Shukla (2000) concluded that the cost of large-scale power generation from biomass is competitive with coal -based generation (or electricity from the grid) only in situations of low biomass fuel cost. Similar conclusion was also arrived at by Faiij and Meuleman (1997); for the case of the Netherlands, they concluded that cost of electricity produced from short rotation crops (SRC), willow, would be roughly twice the cost of electricity produced from coal. This explains why most of biomass fuelled power generation capacity in the USA is based on a cheap fuel, i.e. waste wood. Similarly, practically all the biomass energy plants installed by the EC-ASEAN COGEN Programme (an economic cooperation programme between the European Commission and the Association of South-East Asian Nations coordinated by the Asian Institute of Technology, Bangkok, Thailand) are also based on cheap fuels, residues and wastes.

One important reason why coal-based electricity generation appears to be significantly lower compared with biomass is that external costs of energy systems are not considered in calculating generating costs. Faiij and Meuleman (2000) concluded that, if external damage costs are taken into account, the costs of electricity based on SRC and coal would be comparable.

## B. Current use

1. Developing Countries:

Biomass provides basic energy requirements for cooking and heating of rural households and for process in a variety of traditional industries in developing countries. Use of biomass fuels is also well established in agro-processing and wood processing industries.

In most developing countries, the share of traditional fuels in the total national energy use has been falling (see Table 3). This is mainly due to rapid increase in commercial energy consumption in these countries. However, the magnitude of biomass energy consumption in most of these countries has been actually rising.

A study on consumption of biomass fuels was carried out in seven Asian countries within the framework of the Asian regional research programme in energy, environment and climate (ARRPEEC) funded by Swedish International Development Co-operation Agency (Sida). The study showed that 70 - 98% of the total biomass is consumed in the domestic sector in the selected countries (see Table 4).

In general, biomass energy uses in developing countries are characterized by low efficiency so that the biomass fuels used could potentially provide a much more extensive energy service than at present if these were used efficiently. For example, new stove designs can improve the efficiency of biomass use (and reduce biomass consumption) for cooking by a factor of 2 to 3 compared with traditional biomass fired stoves. Similarly, efficiency of biomass fuel use in certain industrial plants, for example, sugar mills, can also be improved substantially.

Bhattacharya et al. [1999] estimated the total saving potential of biomass fuels through efficiency improvements in the seven selected Asian countries to be 326 million tonnes (Mt) annually (see Table 5). Also, the total saving potential of all biomass fuels through substitution of all traditional stoves currently in use by improved stoves in the selected countries was estimated to be around 296 million tonnes per year. The saving potential of fuelwood alone in the domestic sector is around 152 million tonnes; this is about 43% of the total fuelwood use in the domestic sector.

2. Developed countries

Biomass energy use in developed countries is mainly for space heating and power generation. As shown in Table 6, the share of traditional fuels in total energy use in these countries has been rising quite significantly. For example, the share rose more than tenfold in Denmark during 1980-1997.

## C. Barriers

A number of modern BETs are still in early stages of development and commercialization. Most of these face a wide range of barriers, which must be removed for promoting and facilitating their commercialization.

The prevailing low price of oil in the international market has seriously eroded the financial viability of many RE systems. In fact, this has already adversely affected many on-going renewable energy programs, resulting in significant scaling down in some cases, for example, the ethanol program in Brazil.

The situation is further aggravated by subsidy given to fossil fuels in many countries. It has been pointed out that worldwide government subsidies for conventional energy was US$ 250-300 billion per year in the mid-1990s (de Moor and Calamai, 1997). In India, the Government spent about US$ 1.5 billion annually for subsidizing kerosene in the late 1990s (Forsyth, 1998). Subsidy for fossil fuels distorts market in favour of these fuels; for example, this gives diesel generators an unfair advantage over gasifier engine systems.

The major barriers to biomass energy in developed countries appear to include: 1. information - since there is a lack of understanding of using biomass for energy in many countries; 2. risk - mainly those associated with unproven fuel supply and conversion technologies; 3. financial - since the cost of energy from biomass is normally higher compared with fossil fuels; 4. market characteristics - mainly arising out the network involving farming/forestry communities and power producers; and 5. insufficient policy support for energy crops.

## D. Outlook

The pace of commercialization of biomass energy technologies and future use of biomass energy will depend on action taken to remove the barriers as mentioned above.

In developing countries, future biomass energy use is likely to be characterized by improvements in efficiency and environmental performance of traditional energy devices. Some of the traditional biomass energy users are likely to switch over to commercial energy, particularly for cooking. On the other hand, climate change and other environmental concerns and related developments are expected to promote utilization of cheap biomass, particularly wood- and agro-processing residues. Further utilization of these as well as plantation biomass is likely as the climate change debate intensifies and/or the prices of fossil fuels show signs of escalation.

Table 3. Traditional Energy Use in developing countries

| Country | Traditional fuel (% of total energy use) | | Estimated Increase in traditional energy consumption between 1980-1998 |
|---|---|---|---|
| | 1980 | 1997 | |
| Brazil | 35.5 | 28.7 | 15.0% |
| China | 8.4 | 5.7 | 14.6% |
| India | 31.5 | 20.7 | 11.3% |
| Malaysia | 15.7 | 5.5 | 11.6% |
| Nicaragua | 49.2 | 42.2 | 27.6% |
| Peru | 15.2 | 24.6 | 124.0% |
| Philippines | 37.0 | 26.9 | 13.2% |
| Sri Lanka | 53.5 | 46.5 | 21.6% |
| Sudan | 86.9 | 75.1 | -19.4% |
| Tanzania | 92.0 | 91.4 | 31.8% |
| Thailand | 40.3 | 24.6 | 46.0% |

Source of data: World Bank (2002)

Table 4: Consumption of biomass in selected Asian countries (Bhattacharya an Salam, 2002).

| Country | Base year | Domestic Sector | | Industrial and Commercial sector | |
|---|---|---|---|---|---|
| | | Amount (Mt) | Percentage | Amount (Mt) | Percentage |
| China | 1993 | 458.0 | 94 | 29.4 | 6 |
| India | 1991 | 231.5 | 78 | 65.9 | 22 |
| Nepal | 1993 | 15.1 | 98 | 0.3 | 2 |
| Pakistan | 1991 | 48.5 | 78 | 14 | 22 |
| Philippines | 1995 | 18.6 | 70 | 8.1 | 30 |
| Sri Lanka | 1993 | 10.0 | 87 | 1.5 | 13 |
| Vietnam | 1991 | 29.1 | 91 | 2.9 | 9 |

Table 5: Estimated biomass saving potential (Million tonnes year$^{-1}$) through efficiency improvements in the selected countries (Bhattacharya et al., 1999).

| Country | Base year | Type of biomass | | | |
|---|---|---|---|---|---|
| | | Fuelwood | Agri-residues | Animal dung | Charcoal |
| China | 1993 | 51.6 | 77.2 | 2.9 | - |
| India | 1991 | 69.5 | 20.8 | 32.3 | 0.5 |
| Nepal | 1993 | 3.1 | 1.2 | 0.8 | - |
| Pakistan | 1991 | 17.5 | 7.3 | 8.3 | - |
| Philippines | 1995 | 7.6 | 2.3 | - | 0.3 |
| Sri Lanka | 1993 | 2.6 | 0.5 | - | - |
| Vietnam | 1991 | 15.8 | 3.9 | - | 0.1 |
| Total | | 167.7 | 113.2 | 44.3 | 0.9 |

Future use of biomass in developed countries for heat is likely to depend on development of fossil fuel costs with respect to biomass fuels and whether environmental costs of energy use are taken into account. Thus, it has been suggested that the use of biomass in European Union in 2010 may be double the amount used in 1995 if 'full social cost' of energy use is considered (Source: http://europa.eu.int/comm/energy_transport/atlas/htmlu/renewables.html)

There is a growing interest in electricity generation from biomass worldwide; thus, in Asia it is projected that by 2015, China will have between 3,500 and 4,100 MW of biomass based capacity and India will have 1,400-1,700 MW (http://www.eren.doe.gov/biopower/basics/ba_bmo.htm).

Table 6: Traditional energy use in selected developed countries.

| Country | Traditional fuel (% of total energy use) 1980 | 1997 |
|---|---|---|
| Denmark | 0.4 | 5.9 |
| Japan | 0.1 | 1.6 |
| Germany | 0.3 | 1.3 |
| Netherlands | 0.0 | 1.1 |
| Sweden | 7.7 | 17.9 |
| Switzerland | 0.9 | 6.0 |
| United Kingdom | 0.0 | 3.3 |
| USA | 1.3 | 3.8 |

Efficiency improvements of existing energy systems - particularly in developing countries and utilization of huge quantities of biomass - mostly in the form of agricultural residues and wastes, which are currently disposed by burning or dumping could potentially increase the energy supply from biomass substantially. Significant additional increase in biomass energy supplies should be possible through plantations, probably in degraded land. Biomass plays important roles in energy scenarios developed by a number of international organisations (see Table 7). More recently, using scenarios presented in the IPCC's Special Report on Emissions Scenarios (SRES) as baselines, post-SRES mitigation scenarios have been developed. Biomass plays important roles in these scenarios; the upper limit of primary biomass use in post-SRES group of scenarios in the year 2050 is 328 EJ. This may be compared with world primary conventional energy consumption of about 370 EJ in 2000. Although scenarios do not represent prediction of the future, they suggest what can be realized if appropriate policy measures are implemented; thus biomass can be seen to have the potential to play a vital role in meeting world energy demand in the future**.**

Table 7. Contribution of Biomass in Alternative Scenarios (EJ)

| Scenario | Year 2025 | 2050 |
|---|---|---|
| EPA (RCWP, 1990) | 136 | 215 |
| Shell (1996) | 85 | 200-220 |
| IPCC (1996) | 72 | 280 |
| Johansson et al. (1993) | 145 | 206 |

## III. BIOMASS DENSIFICATION

### A. Introduction

Utilization of agricultural and forestry residues is often difficult due to their uneven and troublesome characteristics. This drawback can be overcome by means of densification, i.e. compaction of the residues into products of high density and regular shape. Densification has aroused a great deal of interest worldwide in recent years as a technique of beneficiation of residues for utilization as energy source.

Depending on the type of equipment used, densified biomass can be categorized into two main types: briquettes and pellets. Briquettes are of relatively large size (typically 5-6 cm in diameter and 30-40 cm in length) while pellets are small in size (about 1 cm in diameter and 2-4 cm in length).

Densified biomass produced in developing countries is mostly in the form of briquettes, which are used directly to substitute fuelwood or for carbonizing to produce briquetted charcoal; use of pellets so far appears to be insignificant. Because of small and uniform size, pellets are particularly suitable for automatic auger-fed combustion systems; densified biomass used in developed countries is mostly in the form of pellets.

## B. Densification technologies

Two common types of briquetting presses employed in developing countries are heated-die screw press and piston press. It appears that heated-die screw press technology was invented in Japan in mid-1940s. By now, the technology has spread to most of its neighbouring and nearby countries, particularly Korea, China, Taiwan, Vietnam, Thailand, Malaysia, Philippines, Bangladesh, etc. where heated-die screw-press briquetting machines are used almost exclusively. Also, the design of screw-press briquetting machines appears to have evolved and been adapted to suit local conditions in different countries.

The piston press technology is the dominant technology in India, Brazil and Africa. While these are locally made in India and Brazil, the African machines appear to be mostly imported. Compared to piston-press machines, heated-die screw press machines have smaller capacity but produce stronger and denser briquettes. Screw press technology is therefore more suitable if the briquettes are to be carbonized to obtain briquetted charcoal.

Besides, conventional binderless briquetting, low-pressure cold briquetting using binder has also been tried in some places. Most noteworthy among these is the carbonization-briquetting process, in which biomass is first carbonized and the resulting charcoal is briquetted using a suitable binder. The process has been tried for cotton stalk in Sudan and coffee husks in Kenya; limited use of this technique has been reported in India and Nepal. Briquetting of bagasse using molasses as binder has been reported to have had limited success in Sudan.

Another low-pressure binderless briquetting process involves mixing pulverized chopped and decomposed biomass with water into a pulp. The pulp is pressed inside a perforated pipe to get 4-inch diameter cakes, which are sun-dried to get briquettes (Stanley, 2002). The basic press is made on site and the product is normally of lower density compared with conventional briquettes. A non-profit organization, Legacy Foundation, is currently involved in dissemination of the technology.

Briquette made from a mixture of pulverized coal, biomass and slaked lime has been introduced by a Japanese company in two Asian countries, China and Indonesia. The briquettes, called coal-biomass briquettes are produced by using a roll-press. It is claimed that the use of the desulfurizing agent (slaked lime) and biomass results in cleaner combustion of the briquettes in stoves and less of ash compared with coal or coal briquettes (Kobayashi, 2002).

As indicated earlier, pelletizing is the major densification technology employed in developed countries. Capacity of these plants is much larger, being in the range 1-30 tons per hour.

## C. Raw materials for biomass Densification

The most common raw materials for heated-die screw-press briquetting machines are saw dust and rice husk. Some other raw materials, e.g., coffee husk, tamarind seeds, tobacco stems, coir pith and spice waste have also been used in India (Vempaty, 2002). Sawdust is practically the only raw material used for producing briquettes, which are subsequently carbonized; it is the dominant raw material in Malaysia, Philippines, Thailand, and Korea. On the other hand, rice husk is the only raw material used in Bangladesh.

Piston press briquetting machines use a wide range of pulverized raw materials; in India, these include saw dust, ground nut shell, coffee husk sugar cane bagasse, cotton stalks, sun flower stalks, spent coffee waste etc. Peanut shell and cotton stalk appear to the most important raw materials in Africa.

The raw material mostly used in developed countries is sawdust and wood wastes.

## D. Status of Biomass Densification

1. Biomass Densification in Asia

*Bangladesh:* Biomass briquetting is a relatively recent development in Bangladesh. The briquetting machines are of heated-die screw press type with a capacity of about 75 kg/hr, similar to briquetting machines commonly used in a number of other countries of the region, e.g. Thailand, Malaysia and South Korea.

In Bangladesh, briquetting technology has found remarkable acceptance over the last few years. At present, about 1000 briquetting machines appear to be operating in the country. The cost of a locally made briquetting machine in Bangladesh has been reported to be about Taka 50,000 (60 Taka ~ 1 US$). The technology appears to have been developed by the local entrepreneurs without any support from the government or donor agencies. Bangladesh Institute of Technology, Khulna is currently working on a research and development project funded by the Swedish International Development Cooperation Agency (Sida) to improve and further promote briquetting technology in Bangladesh.

*China:* The technology of biomass densification by means of screw presses is mature in China, while piston press briquetting machines are also being developed presently. The capacity of screw press briquetting machines is about 100-120 kg/hr. The raw materials commonly used for briquetting are ricehusk, sawdust and agricultural residues. About half of biomass briquettes produced is directly used as boiler fuel as substitute of coal, the other half being used to make charcoal. Generally, 3 tons of briquettes produce one ton of charcoal. The heating value of the charcoal is about 30,000 kJ/kg.

Attempts are being made in China to solve two problems associated with production and utilization of biomass briquettes. One is the short life of the screw of the briquetting machine and the other is emission of polluting gases from the process of making charcoal from briquettes.

Currently, there are about 600 biomass briquetting machines operating in China.

In addition to biomass briquettes, coal-biomass briquettes mentioned above are also produced in a number of locations in China. A plant of capacity 600,000 tons per year is currently under development in one city, Anshan ( Source: http://www.unirex-jp.com/engbiocoal/engbiocoal.htm).

*India:* About 70 biomass briquetting machines were installed in India by 1995; since then briquetting has been gaining acceptance slowly but steadily. Two types of briquetting presses are common in India, piston presses and heated-die screw presses. The capacity of piston presses normally lies in the range 400-2000 kg/hr (Vempathy, 2002); the number of machines of this type installed so far is about 150. Heated-die screw-press briquetting machines are also available commercially; the number of machines of this type installed so far is about 60. One manufacturer offers preheated biomass briquetting systems.

Indian Renewable Energy Development Agency Limited (IREDA) is a Public Limited Government Company established in 1987, under the administrative control of Ministry of Non-Conventional Energy Sources (MNES) to promote, develop and extend financial assistance for renewable energy and energy efficiency/conservation projects. IREDA support for briquetting in the form of loans since its inception till March 2001 was INR 174 million (47 INR ~ I USD). The largest plant financed by IREDA has a capacity of 12.2 tonnes per hour. With assistance of USAID, three briquetting plants have been set in Rajastyan state of India. These plants use mustard stalk as the raw material and combined capacity of about 45,000 tonnes per year; 12-14 briquetting factories with a capacity to produce 200,000 tons per year are being planned.

*Myanmar:* In Myanmar, biomass briquetting technology is in the initial stages of development. There is currently only one manufacturer who has developed a small (10 hp) screw press briquetting machine. By 1995, ten of his machines were sold in the country (Win, 1996).

*Nepal:* Two types of briquetting processes were introduced in Nepal in 1980s: carbonization-briquetting process, basically of Indian origin, and Screw Press briquetting.

The first carbonization-briquetting type of plant was installed in 1982; it had an annual production capacity of 900 tons. Two more such plants of capacity 1200 tons and 600 tons per year were established by 1984. These plants essentially consisted of a pyrolyser, a blender, an extruder and a drier. The pyrolyser was in the form of a U-shaped tube through which the granular biomass material moved while being heated externally by burning a part of the pyrolysis gas; the powdered charcoal thus produced was next briquetted using a suitable binder and dried (Shakya, 2002 and Singh, 2000).

Screw Press briquetting process was introduced in Nepal in mid-1980s through a Japanese funded demonstrated program. Later, a number of screw-press type of briquetting machines were imported from Taiwan.

Initially, rice husk was practically the only raw material used for briqueeting and it was available almost free of cost; this created a lot of interest in briquetting and establishment of more briquetting plants upto about 1991. Later, cost of rice husk increased due to demand for alternative uses; because of this and a number of other reasons many of the briquetting plants, including practically all of the carbonization-briquetting type, were ultimately closed down. At present only six briquetting plants are in operation in Nepal (Shakya, 2002).

Apart from large-scale commercial briquetting, small-scale biomass carbonization-briquetting to produce "beehive briquettes" from waste wood, leaves, twigs and residues appears to found some acceptance in Nepal.

*Philippines:* In the Philippines, currently, about 14 commercial biomass briquette producers appear to exist. Sawdust and ricehusk are mainly used for briquetting (Elauria and Cabrera, 1996).

*Thailand:* The briquetting machines used in Thailand are of heated-die screw press type, the capacity of a machine being around 100 kg/hr.

In Thailand, commercial briquetting is limited to two raw materials, e.g. ricehusk and sawdust. In mid-1988, there were nine briquetting plants in Thailand. Two of these produced briquettes from ricehusk involving a total of 9 machines while seven produced sawdust briquettes with a total of 44 machines.

No significant change in the number of briquetting plants/machines appears to have taken place in the 1990s so far. Most of the biomass briquettes produced in Thailand is carbonized to obtain briquetted charcoal for domestic as well as export markets.

2. Biomass Densification in Africa

According to Karekezi (2002), recent years have seen an upsurge of interest in biomass briquetting. According a recent report "there are large-scale functioning briquetting plants in Ethiopia, Kenya, Malawi, Uganda, Sudan, Zambia and Zimbabwe" (OSCAL, 2002). Biomass briquettes have found limited application certain other countries as well, e.g. Cameroon, Eritrea, Ghana, Rwanda, Senegal, Tanzania etc. However, briquetting experience in Africa appears to be limited to certain pockets in most countries.

The raw materials most commonly briquetted in Africa are coffee husks and groundnut shells; sawdust and cotton stalks are also used to a limited extent. A 4000 ton per year pilot cotton stalk briquetting plant was established in Eritrea in 2000 (http://igadrhep.energyprojects.net/GetDoc.asp?DocumentID=6). Bagasse briquetting appears to found some success in Sudan and one more raw material, papyrus reed, has been tried in Rwanda.

Practically all types of densification machines have been tried in Africa; these include imported screw presses for briquetting sawdust in Eritrea, Malawi, Tanzania and Ghana, piston presses used for briquetting coffee husk in Kenya and groundnut shell in Sudan, and pellet presses for densification of groundnut shells in Zimbabwe and Senegal and sunflower husk in Zambia. ABC Hansen A/S, a group of companies headquartered in Denmark, appears to have established nineteen briquetting plants in several African countries, e.g. Burkina Faso (1), Eritrea (1), Ethiopia (7), Gambia (1), Ghana (1), Kenya (2), Nigeria (1), Rwanda (1), Sudan (4), Zambia and Zimbabwe; it appears that more than half of these are still in operation.

Besides, conventional binderless briquetting, low-pressure cold briquetting using binder has also been tried in some places. The carbonization-briquetting process has been tried for cotton stalk in Sudan and coffee husks in Kenya. Briquetting of bagasse using molasses as binder has been reported to have had limited success in Sudan.

Low-pressure binderless briquetting process of Legacy Foundation mentioned above has been attempted in some African countries, notably Kenya and Malawi (Stanley, 2002).

3. Biomass Densification in Latin America

In Latin America, densification is best established in Brazil, where briquetting was introduced around 1980. As reported by Eriksson and Prior (1990), initially the machines were sold to rice mills while later wood factories became the main users; the experience is quite similar to that of some Southeast Asian countries, for example, Thailand. By 1990, about 200 machines were installed in Brazil; there were practically all locally made and of piston-press type (Eriksson and Prior, 1990). Briquetting appears to be making quite steady progress in Brazil; according to UNECE (1996) some 30,000 tonnes of briquettes were consumed monthly in Sao Paulo state alone in mid-1990s. It is estimated that the current annual production of briquettes in Brazil is around 1,000,000 tons; a number of raw materials are used for this purpose, e.g. cotton wastes, rice husk, bagasse, saw dust, coffee husk sunflower husk, paper waste straw etc (Filho, 2002).

It appears that densification is not common in most other countries of Latin America, although briquettes are known in Haiti since the 1980s (Saint-Cyr, 2002). The low-pressure binderless briquetting process of Legacy foundation mentioned above has been demonstrated in Haiti and Nicaragua. It appears that two more attempts to introduce biomass briquettes in Nicaragua were made in the past. One of these used cotton trashes as the raw material, while the used sawdust; the briquettes were found to be costlier than fuelwood and did not find market-acceptance (Engracia, 2002).

4. Biomass Densification in developed countries

Among the developed countries, Japan, where the heated-die screw-press technology was invented, appears to be first country to introduce biomass densification. According to Grover and Mishra (1996), there were about there were 638 plants in Japan engaged in manufacturing sawdust briquettes in 1969. Production of densified biomass in the form of pellets and briquettes in Japan does not appear to be significant at present, the current annual pellet production being about 2500 tons (Yokoyama, 2002).

North America (USA and Canada) and Sweden, where pellet production in 1998 was about 680,000 and 470,000 tonnes respectively, are the two largest producers of wood pellets at present. In Sweden, the first plant started production in 1982 and the present installed capacity is about one million tons per year. The potential of raw materials, saw dust and other wood-processing wastes, in Sweden is also about 1 million tons so that there is not much scope to increase installed capacity without diversifying in terms of raw material. Therefore, any significant rise in future pellet demand may have to met mostly through imports; already Sweden imports about 100,000 tonnes of pellets annually.

In the USA, wood pellet industry became established in mid-1980s. At present, there are about 60 pellet manufacturers in the country.

Pellet production in 1999 in Austria, Denmark and Norway was 41,000; 150,000 and 20,000 tons respectively (Malisius, 2000). Estimated pellet production in Finland in 2001 was 90,000 tons (Alakangas, 2001).

In Germany, commercial pellet production started in the last few years; pellet use is in early stage but interest is growing fast.

## E. Prospects of Biomass Densification

1. Current use of Densified biomass

a. Developing countries

In general densified biomass is not cheap and cannot compete with fuelwood in developing countries. For example in Kathmandu, the capital of Nepal, the price per kg of briquettes is about three times the cost of fuelwood (Shakya, 2002). However, although briquettes are normally costlier compared with fuelwood, these have found some acceptance under some special situations:

*Reliable supply of fuel.* Reliability of fuel supply appears to of particular importance in case of some users. Some sort of contract/understanding between the briquette supplier/manufacturer and user can establish a niche market for briquettes. Examples of this type inlcude the use of briquettes in tea-stalls in Bangladesh and tourist destinations in Nepal.

*Consistent fuel quality.* The most common alternative to briquettes is fuelwood, which is characterised by uneven shape and size; also the moisture content of wood may vary widely making estimation of the fuel quantity needed for a batch task somewhat difficult and combustion quality unpredictable.

*Eco-friendly image.* Biquettes often have the image of an eco-friendly fuel; this appears to partly responsible for their use in star hotels in Nepal.

Superior quality: Briquettes and charcoal produced from briquettes are superior to fuelwood and wood-charcoal respectively for certain applications. While fuelwood may need further preparation, for example sizing and drying before actual use, briquettes are directly used and can be easily broken to pieces of desired length if needed. A piece of biomass briquette burns for a longer period compared with a piece of fuelwood of comparable size; this appears to be another reason why briquettes are used in star hotels in Nepal. A survey carried out under the guidance of the author in Thailand established that food-vendors preferred briquetted charcoal obtained from carbonization of sawdust briquettes over wood-charcoal because of its superior properties, e.g. longer lasting fire, consistent quality and non-sparking combustion (Bhattacharya and Shrestha, 1990).

Low price: Free raw material, low-cost briquetting technique and special situations may make briquettes cheaper than alternative fuels. This appears to be the reason of market acceptance of bagasse briquettes in Sudan. In India, briquetted biomass is competitive in places where coal is expensive because of long transportation distances involved (Vimal, 2002).

b. Developed Countries

In developed countries densified biomass is mainly used for space heating. In Sweden about 40% of pellet produced in 1998 was used in a single large district-heating plant and the rest was used in medium sized boilers and stoves. In Denmark, there are 37 wood pellet fired district-heating plants. In Austria, pellets are used for central heating of single-family houses, small district heating systems and stoves. In Norway district heating is not very common and firing stoves is likely to emerge as the major application of pellets. In USA and Canada, pellets are mostly used in residential buildings for firing stoves. Pellets have been introduced in Finland and Germany only recently.

2. Barriers to Densification

a. Developing countries

The raw materials for briquetting, e.g. residues and wastes, are generated in huge quantities each year; much of the annual generation remains unutilized and often presents a problem of disposal at a cost. Therefore biomass briquettes appear to be a lucrative product of immense potential. For example, it has been estimated that the residues available in Bangladesh can potentially support about 18,000 briquetting machines (Moral, 2001). This may be compared with about 1000 machines actually operating at present showing that current installation of briquetting machines is far below the technical potential. The situation is quite similar in practically all developing countries and is because of the fact that briquetting faces a wide range of barriers, which must be removed for promoting its wider acceptance.

According to a study carried under a project of the United Nations Economic and Social Commission for Asia and the Pacific in 1998 on commercialization of renewable energy technologies for sustainable development, the barriers to biomass briquetting in Bangladesh included lack of awareness about the technology (among potential entrepreneurs), lack of stable supply and price of raw materials, operation and maintenance problems, lack of trained technicians etc. In Myanmar, the barriers included lack of appropriate financing mechanism (for business establishment), lack of availability of suitable systems/machines. The above barriers appear to exist in other developing countries as well. Based on a study of the briquetting industry in India, frequent failures of power supply in some developing countries may also present a barrier to smooth and profitable operation of briquetting plants (Clancy, 2002)

High cost of briquettes compared with fuelwood in most developing countries is also a barrier to acceptance of briquettes in most developing countries.

In many countries, briquetting is a new technology and there are instances of failures. As a result, investments for establishing briquetting plants is often perceived as risky.

b. Developed countries

The major barriers to pellets are different in different countries, although some problems appear to be common, e.g. bias in favour of conventional fuels and energy systems, technical problems, need for significant storage space, initial investment needed for change-over from the existing heating system, lack of user awareness etc. High cost of pellet price is a barrier in some countries; for example, the cost per unit of energy was higher for pellets compared with natural gas or heating oil in USA in 1997.

3. Future Prospects

The amount of raw materials potentially available for densification is huge in developing countries. For example, the amount of agricultural and agro-industrial residue that either remains unutilized or is used inefficiently in India alone is about 400 million tons per year. However, actual briquette production in developing countries is far below the technical potential based on availability of raw materials. The future penetration of briquetting technology in these countries will largely depend on the extent of removal of the barriers pointed out above. The briquetting industry enjoys support from government agencies in only a few countries, e.g. India, where IREDA provides loans for briquetting plants amounting upto 70% of the project cost. Without active government support and intervention, no significant growth of the biomass briquetting industry is likely to occur in the near future.

In the case of business as usual (with no significant new support/incentive from the government or other sources), use of biomass briquettes in special situations as pointed out above is still expected to increase in the future, albeit slowly, with the dissemination of information regarding briquetting technology and the existing plants.

Markets for briquettes may also develop in the future in places where fuelwood prices are increasing rapidly.

Prospects of renewable energy technologies, including biomass densification, appear to be improving as a result of growing concerns regarding climate change. Thus, a pilot densification project funded and supported by Global Environment Facility's Small Grants Programme has been implemented in Bhutan recently (Neopaney, 2002). In India, a biomass briquetting project has been proposed recently for consideration under South Asia – Canada Regional Initiatives on Climate Change. More projects of this type are likely to be initiated as the climate change debate intensifies.

The developed countries, which have committed themselves to reduce greenhouse gas (GHG) emissions according to the Kyoto Protocol, are introducing programmes to promote renewable energy in general. Prospects of densified biomass will, no doubt, improve as a result for consumption in both domestic and export markets. Thus, Malisius et al. (2000) projected that pellet production in Norway would rise from 10,000 ton in 1998 to 100,000 tons per year in two years.

## III. CONCLUDING REMARKS

Interest in modern biomass energy technologies has been growing worldwide in recent years. The share of biomass in the total energy consumption has been rising in developed countries. In most developing countries, the magnitude of biomass energy consumption is rising although the share of traditional fuels in the total national energy use has been falling.

The current market price advantage of fossil fuels, particularly coal, with respect to biomass fuels would substantially diminish if the environmental costs were considered in pricing of fuels. Also, since one of the main reasons behind the current interest of renewable energy is the environmental impact of large-scale use fossil fuels, it appears irrational that this concern is normally not reflected in pricing of energy today. With a fair pricing of energy, biomass based energy would become viable under a wide range of situations and the pace of commercialization biomass energy technologies would accelerate.

Although densification appears to have aroused a great deal of interest in recent years, actual production of densified fuels is still very low compared with their technical potential.

Densified biomass produced is mostly in the form of briquettes in developing countries and in the form of pellets in developed countries.

Biomass densification faces a wide range of barriers, which must be removed for promoting its wider acceptance.

Growing global concerns regarding climate change and related developments are likely to improve the prospects of biomass energy technologies, including densification in the near future.

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**References:**

Alakangas, E. and Paju, P. (2001), Wood pellets in Finland - technology, economy and market, OPET Report 5, OPET, Finland.

Berg, Christoph, World Ethanol Production, July 31st, 2001, retrieved 11 August, 2002 from http://www.distill.com/world_ethanol_production.htm.

Bhattacharya, S.C. and P.A. Salam, Low Greenhouse Gas Biomass Options for Cooking in the Developing Countries, Biomass and Bioenergy, Vol. 22, pp 305-317, 2002.

Bhattacharya, S.C., R. A. Attalage, M. Augustus Leon, G.Q. Amur, P. Abdul Salam and C. Thanawat. Potential of biomass fuel conservation in selected Asian countries. Energy Conversion & Management, 1999. 40:1141-1162.

Bhattacharya, S.C. and Shrestha, R.M. (1990), Biocoal Technology and Economics, Regional Energy Resources Information Center, Asian Institute of Technology, Thailand.

Brown, R.C., J. Colleti, and A. Hallam, Factors Influencing the Adoption of Biomass Energy Systems: An Evaluation for Iowa, http://webbook2.ameslab.gov/techreports.htm, 11 May, 2001.

Clancy, J. (2002), Barrier to innovation in small-scale industries: Case study from the briquetting industry in India, retrieved 12 August 2002 from http://www.intech.unu.edu/events/ceres_15may2002/clancy.pdf.

de Moor, A. and P. Calamai. 1997. Subsidising Unsustainable Development – Depleting the Earth with Public Funds, as reported by Reddy et al., 1997.

Elauria, J.C. and M.I. Cabrera (1996), Biomass Briquetting in the Philippines, in *Proc.International Workshop on Biomass Briquetting*, New Delhi, India (3-6 April 1995), RegionalWood Energy Development Program in Asia, GCP/RAS/154/NET, FAO, 1996.

Engracia, Maria, Prolena, Nicaragua, Personnel communication.

EPA (Environmental Protection Agency, USA), Scenario: Rapidly changing world with stabilizing policies (RCWP), Policy options for stabilizing global climate, Report to Congress, Technical Appendices, 1990

Eriksson, S. and M. Prior (1990), Briquetting of Agricultural Wastes for Fuel, FAO Environment and Energy Paper 11. FAO, Rome.

Filho, Armando Gomes (Sao Paolo, Brazil), 2002, State, of the Art of Briquettes for Energy in Brazil, Personal communication.

Forsyth, T. 1998. Renewable Energy investment and Technology Transfer in Asia, Renewable Energy World, Vol.1, No. 1, pp 48-50.

Grover, P.D. and S.K. Mishra, 1996. Biomass Briquetting: Technology and Practices, Regional Wood Energy Development Programme, FAO, Bangkok

IPCC, Climate Change 1995: impacts, adaptations and mitigations of climate change: Scientific-technical analysis, Intergovernmental Panel on Climate Change Working Group II report, Cambridge University Press, 1996.

Johansson T.B., Kelly, H., Reddy, A.K.N. and Williams, R.H., Renewable Energy: Sources for fuels and Electricity. Island Press, Washington DC, 1993

Junfeng, L. Runqing, H, Li, Z and Zhengmin, Z .2000. Biomass Resources Assessment in China. Asian Regional Research Programme in Energy Environment and Climate Phase II. Unpublished Report. Asian Institute of Technology, Bangkok.

Karekezi, S. (Nairobi, Kenya) 2002, Personal Communication.

Kobayashi, M., 2002, Unirx Co, Ltd, Japan, Personal Communication

Malisius, U., H. Jauschnegg, H. Schmidl, B. Nilsson, S. Rapp, A. Strehler, H. Hartmann, R. Huber, J.Whitfield, D. Kessler, A. Geiblhofer, and B. Hahn, 2000. Woodpellets in Europe. Retrieved August 19, 2002 from http://www.eva.wsr.ac.at/(en)/publ/pdf/pellets_net_en.pdf

MNES. 2002. Ministry of Non-conventional Energy Sources 200102002, Annual Report. India.

Moral, M.N.A, 2001, Development of Biomass Briquetting Systems Suitable for Bangladesh, Proc. National Seminar on Utilization of Renewable Energy in Rural areas of Bangladesh, 9-10 November, 2001.

Neopaney, D. (2002), UNDP, Nepal, Personal communication

OSCAL (Office of the Special Coordinator for Africa and Least Developed Counties), Energy for Sustainable Development of the Least Developed Countries of Africa, 2002, http://www.un.org/esa/africa/energyldc

Reddy Amulya K.N., Robert H. Williams, Thomas B. Johansson. 1997. Energy After Rio: Prospects and Challenges, UNDP.

Saint-Cyr, J.W.C., USAID, Haiti (2002), Personal Communication.

Stanley, Richard, Legacy Foundation, Personal communication, 2002.

Shakya, G.R. 2001. Biomass Briquetting in Nepal, unpublished report.

Shakya, I. 2002. Personal communication

Shell, The evolution of the world's energy system. Shell International Ltd. Group External Affairs. Shell Centre, London, 1996.

Shukla, P.R. 2000. Dendropower and Wood Fuel Production Systems: Economic Analysis and Implementation Strategies, Options for Dendro power in Asia, Report on the Expert Consultation, RWEDP, FAO, Bangkok.

Singh, R.M. 2000. Study on Wear of Screw of Bimass Briquetting Extruder, Nepal Journal of Science and technology Vol 2, pp 83-86.

Turkenburg, W.C. 2000, Renewable Energy Technologies, Chapter 7, World Energy Assessment, UNDP.

UNECE (United Nations Economic and Social Council), Renewable sources of energy with special emphasis on biomass: progress and policies, Report of the Secretary-General, E/C.13/1996/CRP.1

Vempathy, 2002, Personal communication

Vimal, R.K. (2002), IREDA, India, Personal communication

Walter, Arnaldo, Constraints and Perspectives for large-scale electricity production sugar cane residues in Brazil, retrieved 12 August, 2002 from

http://bioproducts-bioenergy.gov/pdfs/bcota/abstracts/30/z140.pdf

Win, U.T. (1996), Production of Biomass Briquettors by Small Scale Industries in Myanmar, in *Proceedings of the International Workshop on Biomass Briquetting*, New Delhi, India, 3-6 April 1995, Regional Wood Energy Development Program in Asia, GCP/RAS/154/NET, FAO.

World Bank (2000), World Development Indicators, 2001

Yokoyama, S. (2002). Director-General, AIST, Chugoku, Japan, Personal communication