Applied Energy, Volume 77, Issue 1, January 2004, Pages 51-67.

Title: **BIOMASS RESOURCES FOR ENERGY IN NORTH-EASTERN BRAZIL**

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Abstract: Due to the high dependency on hydroelectric power generation, Brazil faced a power shortage in 2001. In order to remedy the situation and avoid more severe power crises in the future, the Brazilian Government launched incentive programmes to encourage thermal and renewable power generation. The Programme of Incentives to Alternative Sources (PROINFA) is mainly devoted to the utilisation of biomass. The success of PROINFA depends on the availability of reliable studies for assessing existing biomass resources and the viability of their utilisation for power generation. In this study, energy potentials of main biomass resources in the north-eastern region of Brazil have been assessed. The economy of the north-eastern region of Brazil is heavily dependent on its sugar industry. Biomass available from sugarcane cultivation and processing represent an annual regional energy resource of 40.5 TWh at an average cost of US$ 0.005/kWh. Bamboo, cultivated as a dedicated energy crop, has the second largest annual energy potential of 30.8 TWh at an average cost of US$ 0.009/kWh. Municipal solid waste generated in the region has an annual energy potential of about 16.7 TWh.

Keywords: Biomass, Energy Generation, Sugarcane Bagasse, Bamboo, Black Liquor, MSW, Energy Crops, Process Wastes.

MAIN TEXT

1. INTRODUCTION

North-eastern Brazil is located between the latitudes of 1° 02’ S and 18° 20’ S and the longitudes of 34° 47’ W and 48° 45’ W. It has nine states: Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe and Bahia (see Figure 1). With a land area of 1.558 million km², this region represents 18.23% of the Brazilian territory. According to climatic conditions, land characteristics and vegetation, the region can be divided into four sub-regions: mid-north, forest area, wild-lands and back-lands. With the exception of the forest area, which has a very fertile soil and receives high annual precipitation levels, the average annual temperature in the region is 27°C and the annual precipitation varies from 400 to 600 mm with an intense evaporation rate of 2,500 mm/year [2]. Ninety-one percent of the area of the Northeast Region experience drought periods, which has been associated with El Niño Southern Oscillation (ENSO) [3].

The main river in the region is the São Francisco River, which has been extensively exploited for hydroelectric power production [4]. Currently, ten main hydroelectric power plants and several small units, with a total installed capacity of 10.36 GW, are supplying electricity locally [5,6]. The region has 18.23% of the national population, and the urban population accounts for 69% of the total population. The region has been experiencing an industrial boom since 1990 and is currently responsible for 13% of the national GDP [7]. The sugar industry is a major income source. The favourable climatic conditions for cultivating sugarcane have been recognised since the early days of the Portuguese colonisation. In 2000, cultivated area and production of sugarcane in the region represented 23% and 18.5% of the respective total national figures [8]. Figure 2 shows the shares of the individual States to the region’s sugarcane cultivated area.

Sugarcane is cultivated mainly on flat terrain, while other crops are planted on hills where sugarcane has proven not to be competitive. Beyond its low competitiveness and the old-fashioned harvesting technology employed, the other key problem facing the region’s sugar industry is the moderate drought conditions, such as the most recent events of 1997, 1998 and 1999. To minimise the effects of such phenomena and increase the competitiveness, several sugar mills are investing in irrigation projects. Mechanised harvesting of sugarcane reduces production costs by up to 50% when compared with the traditional manual technique [9,10].

During the period 1990 – 1999, the region’s power consumption increased by 53.5% [6]. The risk of power shortages in the North-east has been predicted since 1998, when studies showed that electricity consumption would exceed its generation by 5% in 2001 [6,11]. Electricity consumption per capita has been increasing rapidly since 1995, and it has been estimated that an investment of US$ 3 billion per year, for the next ten years, is necessary to meet the demand on power [12]. With the restructuring of the Brazilian power-generation sector, natural gas is expected to increase its participation in the primary energy matrix. The originally-planned Brazilian-Government privatisation programme did not progress satisfactorily, forcing the Government to adopt a hybrid-model strategy, with private and public power generators sharing the same market. In 2000, the Government launched the Thermo-electric Priority (PPT) Programme. The Programme of Incentives to Alternative Sources (PROINFA), and the Emergency Programme of Wind Power (PROEÓLICA) were some examples of other programmes launched by the Brazilian Government to encourage the use of renewables in the energy matrix. In 2001, Brazil faced a power shortage. As a result, the Government decided to accelerate the deployment of the PPT Programme and increase the thermal power generation. A new and promising market opened for the sugar mills; bagasse (the waste fibre obtained after the extraction of sugar syrup from the sugarcane) currently represents an attractive biomass fuel, and as a result its market price has increased.

2. ALTERNATIVES TO HYDROELECTRIC POWER GENERATION IN NORTH-EASTERN BRAZIL

The north-eastern Brazil's social and economic development is strongly linked with the São Francisco river and Hydroelectric Company of São Francisco (CHESF) [13]. In 2001, CHESF had its best operational results, with total revenue exceeding US$ 1.2 billions and a profit greater than US$ 268 millions [14]. This profit represented an increase of 15.7% over 2000, despite the power-supply restrictions imposed by the Government. Several studies have proposed modifications in the operation of some of the power plants in order to meet the electric demand during peak periods [11,15,16]. The losses in power generation have been estimated as equal to a power capacity loss of 2.5 MW, which if used by industry, would generate more than US$ 4 million/year [15]. To overcome these losses, the region should import electricity from other regions [11], such as the Amazon region, or install new thermal power plants.

Irrigation, especially in arid areas is necessary to promote agricultural productivity. It increases crop yields by 2.5 to 3 times, increases the value of the land by a factor of 5, and allows for at least 2 harvests and off-season harvests [15]. Studies have indicated that the potential total irrigated area of the São Francisco River valley is 691,000 km² [15]. Considering only areas where the soil is suitable for irrigated crops, within a radius of 60 km from the water source and with a maximum elevation of 120 m, the area to be irrigated is reduced to 81,000 km². The use of water for irrigation for an area bigger than 8 km² would affect the operation of the power-generation plants installed in the São Francisco valley and the power-generation goals needed for the region [15]. Therefore, considering the use of water for irrigation, development projects for the region, and the fact that new power plants will not generate power competitively, it can be concluded that the cost-effective hydroelectric potential of São Francisco River is exhausted [4].

Brazil has a vast potential for power generation from renewable sources. The north-eastern region has notable wind-energy potential and some of it is being utilised for water pumping [17]. Small hydroelectric units are also being explored in the region. The solar intensity in the region is capable of supporting extensive photovoltaic and solar thermal options for some urban and rural applications [2,17]. Biomass is widely available in the region and has been used as an industrial fuel in pulp and paper mills, sugar mills, petrochemical plants, pig iron and steel plants, and other production activities. Incorporation of state-of-the-art, renewable-energy technologies and assessment of relevant international experiences are strategies adopted by the Action Plan for Developing a Sustainable Market for Rural Renewable Energy Services in Brazil [18]. Renewables, particularly wind and biomass, will have a considerable share in future power-generation matrix. Sugarcane bagasse has the greatest potential for the short and medium term due to the strong sugar industry in the region. Other residues (e.g. rice straw and husk, and wood bark) represent other promising sources of biomass.

3. BIOMASS UTILISATION

Biomass fuels can be produced as by-products of the agriculture, forestry and the manufacture of high-value goods (e.g. pulp and paper, sugar and animal feed). According to available sources, biomass can generally be classified into the following categories [19,20]:

- wood residues
- agricultural residues (from crops and farm animals)
- process wastes
- dedicated energy crops
- municipal solid waste (MSW)

As a replacement for fossil fuels, biomass, as an energy source, has the potential to substantially reduce carbon dioxide emissions. Although biomass was considered in the past to be a low-grade fuel, with its use associated usually with poverty, recent utilisation trends and assessment studies indicate that it will play a key role in satisfying mankind future energy requirements in a sustainable manner. Currently, renewables represents about 14% of primary-energy consumption in the world, with biomass being the major contributor (i.e. about 10%) [21,22]. In industrialized countries it accounts for 3% of primary-energy consumption, whereas it represents 35% of primary-energy consumption in developing countries. For 75% of developing-countries' population, biomass represents the most important source of energy.

New techniques have been devised for the utilisation of biomass for energy production, including:

- Thermo-chemical conversion, i.e. combustion, gasification, pyrolysis, liquefaction, hydrothermal upgrading (HTU).
- Biochemical conversion, i.e. fermentation and anaerobic digestion.
- Extraction of vegetable oils.

Combustion can be utilised for power and/or heat generation. This technique is widely applied and has a great potential for improvement. Direct combustion involves the employment of a wide variety of systems including the most common pile burners, stocker (or grate-fired) combustors, and fluidised-bed combustors. Suspension burning, whole-tree energy method and co-firing (especially with coal) are examples of other alternative biomass-combustion technologies that have been devised [22-27]. Gasification involves the partial oxidation of biomass in order to convert it into a gaseous fuel. The gas produced can be employed for the generation of power (via a steam Rankine cycle, a gas-turbine combined-cycle system or an internal-combustion engine) and/or heat. Biomass-gasification technology is still at the demonstration phase, while the second generation of biomass gasifiers is at the development state [22-26]. Pyrolysis is the thermal destructive distillation of biomass in the near absence of oxygen at a temperature of around 500ºC [26]. The process yields charcoal – a more convenient solid fuel, liquids (i.e. tars and oils, or bio-oils) and low-heating value gaseous products. Temperature and heating rate can be adjusted to favour one of these products. Conventional slow pyrolysis is commonly applied for the production of charcoal, with a huge conversion-efficiency range. Pyrolysis for the production of bio-oils is still at the pilot-plant phase and faces some technical barriers. With fast (or flash) pyrolysis, the liquid yield could be up to 70% of the mass of the dry feedstock. Fast pyrolysis at elevated temperatures (i.e. between 800 and 900°C) converts up to 80% of the biomass into a gas rich in hydrogen and carbon monoxide. Liquefaction is a low-temperature, high-pressure thermo-chemical process using a catalyst. However, fast pyrolysis is simpler and more cost-effective [22,27]. HTU, which is a process developed by Shell, converts biomass, at a high pressure and moderate temperatures, in water, to bio-crude. This technique is still in a pre-pilot-plant phase [22].

Ethanol – a liquid fuel – can be produced from biomass by alcoholic-fermentation. Fermentation, based on sugarcane, sugar beet and grains is a commercially-proven technology in many countries, including, Brazil, the USA, France, Germany, Sweden [28-36]. The use of wood as a feedstock, however, is still under development [37-39]. Anhydrous ethanol or neat ethanol (i.e. 95 % ethanol and 5% water by volume) may be used directly as a substitute for petrol in modified engines [29]. Dry ethanol can be mixed with gasoline (as an octane-number enhancer), with 6 to 22% by volume, to produce gasohol [29]. During the peak of the Brazilian Pro-alcohol (Proalcool) Programme (i.e. the substitution of ethanol for petrol in passenger and light-commercial vehicles) in the mid-eighties, the Brazilian automobile fleet had 96% of neat-ethanol-fuelled cars [29]. Ethanol price did not drop as expected and competition with gasoline led to serious problems for the Proalcool programme. Today, ethanol price is 85% of the gasoline price in Brazil [22,39,40]. Anaerobic digestion of biomass is a process that results in the production of biogas (i.e. a mixture of mainly methane and carbon dioxide) cost effectively [41]. Biogas has been produced commercially, employing animal manure, sewage sludge and the organic fraction of municipal solid waste (MSW), in conventional anaerobic digesters or two-phase anaerobic fermentation [41-44].

Vegetable oils, extracted from seeds, crops, nuts, fruits and leaves, can be used as fuels for diesel engines (i.e. as bio-diesel), but they are relatively expensive [22]. Vegetal oils can be used in diesel engines either mixed with diesel fuel or alone without major modifications to the engine. However, some difficulties, such as oil deterioration and incomplete combustion have been reported. Transesterification (i.e. reaction with ethanol or methanol in the presence of a catalyst) of vegetable oils leads to superior diesel-fuel substitutes (i.e. ethyl esters or methyl esters) [45]. In Europe, rape-seed oil methyl ester (RME), produced from oilseed rape is the main substitute fuel, while soybean oil is used in the USA and canola oil in Canada [46].

4. BIOMASS RESOURCES IN NORTH-EASTERN BRAZIL

4.1. Wood Residues, Agricultural Residues and Process Wastes

Wood residues are produced by wood-product industries (i.e. saw mills, paper mills and furniture industry). Agricultural residues from crops include mainly sugarcane leaves and trash and bamboo branches produced during harvesting. Process wastes are produced primarily by sugar mills (in the form of bagasse) and the pulping industry (mainly in the form of black liquor).

In north-eastern Brazil, agricultural residues and process wastes are the main components of the regional biomass resource when compared with wood residues. The region has more than 72 pulp and paper mills. Other wood-product industries (i.e. sawmills and furniture industry) are widely dispersed in the region, and their contribution to large-scale electricity generation is deemed to be not cost-effective. Paper mills utilise bamboo, eucalyptus, sisal, sugarcane bagasse and other fibres. Due to the significant importance of the sugar industry for the local economy, sugarcane bagasse appears to be the logical main source of biomass in north-eastern Brazil. Sugarcane has an average harvesting period of 167 days per year [40]. This period, however, varies depending on climatic conditions. In order to guarantee the continuity of power production in a biomass-based system, other biomass sources with analogous characteristics should be readily available to complement or back up sugarcane bagasse. Bamboo, represents the ideal candidate for this purpose.

Sugarcane can be used for the production of sugar and ethanol. Both products generate bagasse as residue after the sugarcane is crushed for juice extraction, as shown in Fig. 3. The cost of production of sugar in Brazil is low (i.e. under US$ 200/tonne) and the industry employs directly approximately 1.0 million people [40]. When sugar production becomes less attractive, due to the drop in sugar price on the international market, and the ethanol production turns to be more profitable, the producers can switch the production to meet the market expectations. Due to the lack of mechanisation in the north-eastern Brazil, the local industry employs 2.2 times more people than the sister industry in the middle-south region of the country [39,40]. The most remarkable improvements in agricultural and industrial productivity have been achieved in São Paulo (outside the studied area) and Alagoas States due to the adoption of the Proalcool Programme.

The utilisation of sugarcane bagasse for electricity generation purposes in north-eastern Brazil will take advantage of the well established sugar industry in the region. Brazil is today the second largest sugarcane producer in the world [47]. Important improvements were achieved in juice extraction efficiency, vinasse recycling and reduction of fermentation time. Manual harvesting is still the major practice in Brazil; mechanisation could reduce the harvesting costs by at least 30% [9]. However, due to topography limits, mechanised harvesting could cover only approximately 50% of the cultivated area [9]. Burning of sugarcane fields prior to the harvest is also a common practice in Brazil as it improves the throughput in both manual and mechanical harvesting. Burning is now being prevented due to its impacts on the environment and human health. In addition, the losses in cane sucrose are considerable, resulting in ethanol losses in the range of 5.9 to 13.5 m^3 per km^2 of cultivated area [9]. Green harvest for sugarcane brings the possibility of utilising the cane residues for animal feed, as an organic fertilizer or biomass fuel for energy. The combined use of bagasse and sugarcane residues could lower the ethanol costs considerably in Brazil [9,39,48].

The mean yield of sugarcane cultivation in north-eastern Brazil in 2000 was 5.305 ktonnes/km^2 (i.e. between 3.96 and 6.43 ktonnes/km^2) [8]. With about 11,000 km^2 of land area devoted to sugarcane cultivation in 2000, the total production of sugarcane was 58.68 Mtonnes [8] The production of one tonne of sugar requires approximately 8.5 tonnes of sugarcane, while 1.0 m^3 of ethanol requires 12.5 tonnes [40]. The weight of the bagasse produced, at 50% of moisture content, is about 30% of the weight of sugarcane used [49-51]. Accordingly, in 2000, north-eastern Brazil produced about 17 Mtonnes of bagasse.

Physically, bagasse consists of three components (i.e. pith, fibre and rind) mixed in different proportions. In a typical sample, the proportions are about 5% pith, 73% fibres, and 22% rind by weight [52]. Bagasse fibre has up to 54.3% cellulose, 29.7% hemicellulose, and 24.4% lignin [53]. The density of bagasse is around 492 kg/m^3 [52]. Depending on the region where the sugarcane is cultivated, bagasse shows different ultimate analysis [49-51,53-57] (see Table 1). The empirical formula for bagasse, based on the average values for the ultimate analysis is $C_{3.9}H_{6.0}O_{2.7}N_{0.01}$ [58]. The moisture content of bagasse commercialised in Pernambuco State varies from 45% to 52%.

As it is the common practice in the north-eastern Brazil to utilise bagasse for energy production directly from the supplier, without any drying, in this study, the lower heating value on a wet basis will be employed for estimating the energy potential associated with this biomass resource. Dry bagasse has an ash-free gross heating value of around 21.5 MJ/kg [50,53]. By employing the methodology suggested by Quaak et al. [23], assuming typical moisture content of 50% and the average ultimate analysis presented in Table 1, the lower heating value for bagasse was calculated as 8.13 MJ/kg.

Sugarcane leaves are around 1.5 m long, and after being chopped, they have a bulk density of about 30 kg/m^3 [54]. Leaves represent 4% of the sugarcane stalk weight [54]. At least 25% recovery rate of such agricultural residues is possible if mechanisation is implemented in harvesting sugarcane

[9,54]. This results in an estimated potential resource of about 580 ktonnes of sugarcane residues in the north-eastern region in 2000 [8]. However, with only 30% of the cultivated area being subjected to mechanised harvesting, a resource of about 175 ktonnes is more feasible. Agricultural residues from sugarcane cultivation have approximately the same heating value as bagasse [9].

Adopting a heating value of 8 MJ/kg and an annual production of around 17.5 Mtonne of sugarcane bagasse, the total energy potential of bagasse in the north-eastern region of Brazil can be estimated as 140 PJ/year. The additional energy source from utilising agricultural residues from sugarcane plantations is approximately 1.4 PJ/year.

The price of bagasse, produced by the local sugar mills and exceeding their own use for energy, used to be symbolic. However, due to the Brazilian power crisis and recent Government incentives to produce power from biomass, the price of sugarcane bagasse is experiencing a sharp rise. The price practiced by the local market is in the range from US$ 3.5/tonne to US$ 11.84/tonne [59], with an average value of US$ 7.67/tonne. Hence, the maxomum market price of sugarcane bagass is around US$ 1.5/GJ, without transportation costs included. Biomass requires space for storage as well as transportation to power-generation sites. Transportation is a significant cost item in running a thermal conversion system based on biomass. In the north-east of Brazil, the transportation costs of bagasse are 2.4, 4.2, and 6.0 US$/tonne on a wet basis for distances of 50, 100 and 150 km, respectively [59].

Bamboo is the term commonly used to describe a particular taxonomic group of large woody grasses which grows in relatively warm and humid climates, with an annual precipitation of at least 1000 mm. It reaches maturity within 5 years and some species can reach more than 20 metres in height. With the exception of Europe, bamboo grows naturally in subtropical and temperate zones in all continents. In Brazil, there are more than 80 different species of bamboo, but the most common is *bambusa vulgaris*. North-eastern Brazil, in particular, offers the most favourable conditions for bamboo cultivation. Bamboo can be employed for around 1500 commercial applications, including the food, construction, and pulp and paper industry [60]. The largest bamboo commercial cultivation in north-eastern Brazil belongs to João Santos Industrial Group, with more than 108 km^2 cultivated in Maranhão, Paraíba and Pernambuco States [61]. Its two pulp and paper mills (CIB Portela and Itapajé Papéis) produce sack paper and cardboard from this resource.

Agricultural residues of bamboo are generated as a consequence of its handling techniques. After the harvest, the stalks are left in the field for natural drying. Almost all leaves and small branches, which represent 38% of the original weight above the ground for 3-year-old bamboos [62], are lost in the field during the approximately 15-day drying period. The processing of bamboo for pulping also generates waste. Aiming at reducing the NaOH consumption during the pulping process, branches and some parts of the stems unsuitable for pulping, are rejected. Rejects account for approximately 10% of the pulp production in a mill. The two pulp and paper mills in north-eastern Brazil produce 102 ktonnes/year of paper products and require around 300 ktonnes/year of bamboo pulp. They consume about 500 ktonnes/year of cultivated bamboo, which generate 190 ktonnes/year agricultural residues and 30 ktonnes/year process waste.

The characteristics of *phyllostachys nigra*, *phyllostachys bissetii*, and *phyllostachys bambusoides* bamboo species were analysed for energy purposes, whereas those of *bambusa vulgaris* were further analysed for the pulp and paper industry utilisation [60-64]. The life cycle for industrial bamboo coppices in north-eastern Brazil is two years [61,64]. For samples of this age, the moisture content has been found to be 8.79% for *phyllostachys nigra*, 10.66% for *phyllostachys bissetii*, and 12.92% for *phyllostachys bambusoides* [62]. For *bambusa vulgaris* cultivated in North-eastern Brazil, the moisture content is around 35% [64]. The ash content varies between 0.87% and 0.78%

for *phyllostachys nigra*, *phyllostachys bissetii*, and *phyllostachys bambusoides* [62]. For *bambusa vulgaris*, the ash content is around 0.11% [63].

Table 2 shows the ultimate analysis of the four bamboo species studied. Bamboo has low nitrogen and sulphur contents, when compared with coal or other fossil fuels. Therefore, NO_x and SO_2 emissions as a result of its direct combustion are minimal. The silicon content of bamboo species tends to increase with the maturity of the plant. In the Brazilian north-east, the first harvest of bamboo is within 3 years. The following harvests are within intervals of 2 years. From the fifth harvest, the crops must receive more fertilizers to increase the productivity. The low ash and chlorine contents make the bamboo very attractive for combustion applications aiming at electricity generation. The low chlorine content of the bamboo samples means that burning them is unlikely to enhance high-temperature corrosion in biomass combustion systems. From the ultimate analysis presented in Table 2, the empirical formula for *bambusa vulgaris* could be written approximately as $C_{4.3}H_{3.0}O_{2.6}N_{0.03}$ [58]. By employing the methodology suggested by Quaak et al. [23] and an ash-free higher heating value of around 24.5 MJ/kg, the lower heating value on a wet basis for *bambusa vulgaris* was calculated as 12.56 MJ/kg.

By assuming that for bamboo leaves and branches have the same lower heating value as the stems, the potential energy resource associated with bamboo agricultural residues in the region is 2.39 PJ/year. The regional energy potential of bamboo process wastes is estimated as 377 TJ/year.

Cooking, or pulping, liquors are aqueous solutions of chemicals used for delignification of pulping raw materials. Black liquor is the effluent waste from the Kraft pulping process, with 15% solids of which approximately 10% are organic chemicals [65]. Typically, seven tonnes of black liquor are produced for each tonne of pulp [66]. Chemical recovery is the process in which the inorganic chemicals employed are regenerated and recovered for re-use [67]. The process involves concentrating the liquor (typically to a solid content of between 65 and 73%) by evaporation and combustion of the strong black liquor in a furnace or a boiler, and results in the recovery of typically 70% of the chemicals and the generation of a large amount of heat [65-68]. Furnaces are more common for small plants, whereas steam boilers are employed with large quantities of black liquor. The higher heating value for concentrated black liquor is around 14 MJ/kg [65,66,68]. The Brazilian national production of concentrated black liquor (typically at 70% solid content) in 1999 was 9.737 ktonnes, of which only 1.981 ktonnes were utilised for electricity generation employing steam cycles [6]. The total energy potential of black liquor produced in Brazil in 1999 is approximately 136 TJ/year [6]. North-eastern Brazil has several pulp and paper mills that employ the Kraft pulping process. The most important of these are Bahia Sul Celulose, Santo Amaro and Bacell S.A. in Bahia State, CIB Portela, Ondunorte-PE and Ponsa in Pernambuco State, Ondunorte-PB in Paraíba State, and Itapagé S.A. in Maranhão State. However, no representative figures about production of pulp in the north-east of Brazil are available.

4.2. Energy Crops

Energy crops can be divided basically into two types: herbaceous energy crops and short rotation coppice (SRC). Herbaceous energy crops are mostly types of grasses that could be harvested as hay, while SRCs are species that can be grown exclusively for energy production (i.e. eucalyptus and bamboo). Energy crops bring some inconveniences, including [19,20,24]:

- Biomass fuels have their costs raised by the necessity of additional labour and equipment for harvesting, transportation, handling, storage and processing.
- Competition with food and fibre production for land use.

- Removal of additional nutrients from the soil.
- Transportation of large volumes of low energy density fuels to conversion plants.

However, their utilisation brings about the following additional benefits:

- In low latitude countries, some crops have high yields and biomass sources compete cost-effectively with any other fossil fuel.
- Improving the fertility of unproductive saline soils.
- Carbon dioxide sequestration.

Energy crops are usually less harmful to the environment than intensive agricultural practices, due to lower chemical inputs and less soil disturbance and compaction. Land requirements are strongly dependent on biomass crop yields and biomass-to-energy conversion efficiencies. Biomass-to-energy systems always produce considerably more exploitable energy than that required for feedstock production and transportation, and power plant operation [20-22]. The life-cycle CO_2 balance of such schemes, i.e. the excess the CO_2 produced as a result of the operation of a biomass-to-energy facility relative to the CO_2 absorbed by the biomass feedstock, is typically 5% [69].

Similar climatic conditions and soil conditions are required for the cultivation of sugarcane and bamboo. Accordingly, a suitable species of the latter could be cultivated where the topography is not competitive for sugarcane production. *Bambusa vulgaris* is the logical choice as a dedicated energy crop for north-eastern Brazil. In the region, the average growth rate is 7 cm/day [64]. Steep terrain, which is not suitable for sugarcane plantation, could be used for cultivating *bambusa vulgaris* forests. Harvesting of bamboo is a labour-intensive, un-mechanised practice [60-62]. João Santos Industrial Group has been developing new competitive techniques for bamboo harvesting [61].

João Santos Industrial Group reported that the total cost for manual land preparation and planting for sloped areas is around US$ 34,100/km² [61]. For flat areas, the cost drops to around US$ 23,100/km² when the producer makes use of mechanisation. In very steep areas, the cost is about US$ 66,900/km². Fertilisation cost is around US$ 13,100/km² [61]. By assuming a cultivation area consisting of 60% sloped area, 15% flat area, and 25% very steep area, the average total cultivation and fertilisation cost is estimated to be about US$ 55,000/km². By assuming a productivity of 4 ktonnes/km² per year in the fifth harvest [61], the cultivation and fertilisation cost per tonne is US$ 13.75. The cost of harvesting is US$ 11.1/tonne [61]. Accordingly, the total production cost of *bambusa vulgaris* is US$ 24.85/tonne, or US$ 2.0/GJ (based on 35% moisture content and a lower heating value on a wet basis of 12.56 MJ/kg). If it is assumed that bamboo is transported to the utility site at the same prices as sugarcane bagasse, the average cost of bamboo transportation can be estimated as US$ 0.5/GJ. Therefore, the average total cost of bamboo as a dedicated energy crop can be estimated as US$ 2.5/GJ.

By assuming that 20% of the regional area devoted to sugarcane plantation (i.e. 2,211 km²) is not competitive due to topography, and that *bambusa vulgaris* should be planted on this area, the potential yield for this energy crop is 8.84 Mtonnes/year. However, in order to reduce the fertilisation costs, preserve the soil against erosion, and maintain higher bamboo productivity and quality, rotation plans for the land are required [61,64]. The regional energy potential of bamboo as a dedicated energy crop is around 111 PJ/year.

4.3. Municipal Solid Waste

Municipal solid waste (MSW) represents a major source of biomass. Recycling of components of MSW is worthwhile if it confers economic advantage to purchasers of recycled materials or products, saves more fuel, brings about environmental benefits or has lower costs than alternative methods of waste management [70]. Due to the fact that rural areas have a low MSW density, the utilisation of MSW for energy production is more adequate only in/or near large urban centres [71]. Unprocessed MSW in developed countries consists predominantly of paper, plastic and other organics, with approximately 30% moisture content [20]. Despite the fact that the heating value of MSW can vary according to its composition (which reflects the social habits and the economy of the region from which it is collected), the mean lower heating value is around 8 MW/kg [70-72].

North-eastern Brazil accounts for 15% of the national daily amount of MSW produced [73]. Only 0.54% of the MSW generated is incinerated. The most common practice is landfilling, with the waste in some urban areas not receiving any treatment at all. Landfill emission and effluent treatment are becoming a great concern in urban centres of north-eastern Brazil, such as Recife and Salvador. Biogas produced by managed landfills (i.e. landfill gas) can be utilised directly as a low-heating-value industrial fuel or upgraded to a pipeline quality-gas for domestic and transport (e.g. urban transport busses [74]) applications.

MSW incineration can reduce dramatically CH_4 emissions from landfills. Considering that 50% of the total MSW produced annually by the region (i.e. 7.6 Mtonnes [73]) could be treated in energy-from-waste facilities, the potential energy resource is around 60 PJ/year. Further studies should be carried out to establish the costs of collecting and treating MSW for energy production in the region. The total cost for converting MSW into electricity, at 23% efficiency, in São Paulo was estimated to be US$ 80/MWh [74].

5. Conclusions

The north-eastern region of Brazil, as well as the whole country, has increasing power demand. The cost-effective hydroelectric potential of the region has almost been exhausted. The failure to meet the regional power demand will adversely affect the local economy and the region's development programmes. This can increase the gap between such a developing region and the well-developed south-eastern and southern regions of Brazil.

The Government has taken some actions to lessen the dependency on hydroelectric generation in order to avoid future power crises in the country. The PPT programme will focus on thermal power generation using natural gas, while other programmes, such as PROINFA and PROEÓLICA are focusing on power generation from renewable sources. North-eastern Brazil has a considerable potential biomass resource as a result of:

- The region has a great concentration of industries that generates biomass as process wastes or agricultural residues (i.e. sugar mills and pulp and paper industry).
- The climatic conditions are favourable for growing energy crops (i.e. bamboo and eucalyptus).

The success of the PROINFA programme in particular depends on the availability of reliable assessment of biomass resources in the region.

The annual biomass potential of agricultural residue from sugarcane cultivation and bagasses as a process waste is around 146 PJ (or 40.5 TWh). Sugarcane bagasse represents 97% of this total. The cost of sugarcane bagasse as a fuel, neglecting transportation costs, is around US$ 1.5/GJ (or US$ 0.005/kWh), whereas that of sugarcane agricultural residues, considering only transportation costs, is about US$ 0.5/GJ (or US$ 0.002/kWh). The States with the greatest potential for generating electricity from that biomass resource are Alagoas, Pernambuco, Bahia and Paraíba, with annual potentials of 68.2, 39.5, 12.4 and 9.3 PJ respectively.

Bamboo, as a dedicated energy crop, represents a regional potential energy resource of about 111 PJ (or 30.8 TWh), at an average cost of about US$ 2.5/GJ (or US$ 0.009/kWh), if cultivated in areas where sugarcane is not competitive. Current bamboo process wastes and agricultural residues in the region represent an annual energy potential in the order of 3 PJ (or 833 GWh).

MSW appears as the third biomass resource, with an annual energy potential of approximately 60 PJ (or 16.7 TWh). However, further studies are required to estimate its cost as a fuel.

FIGURES

Figure 1

Figure 2

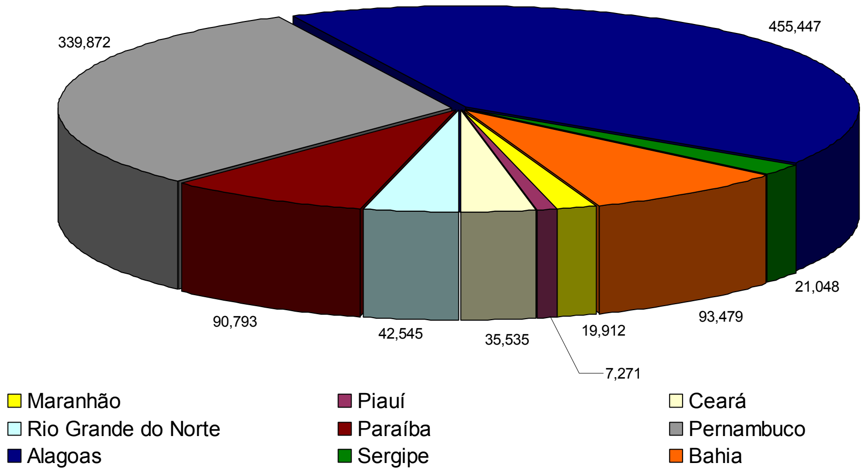
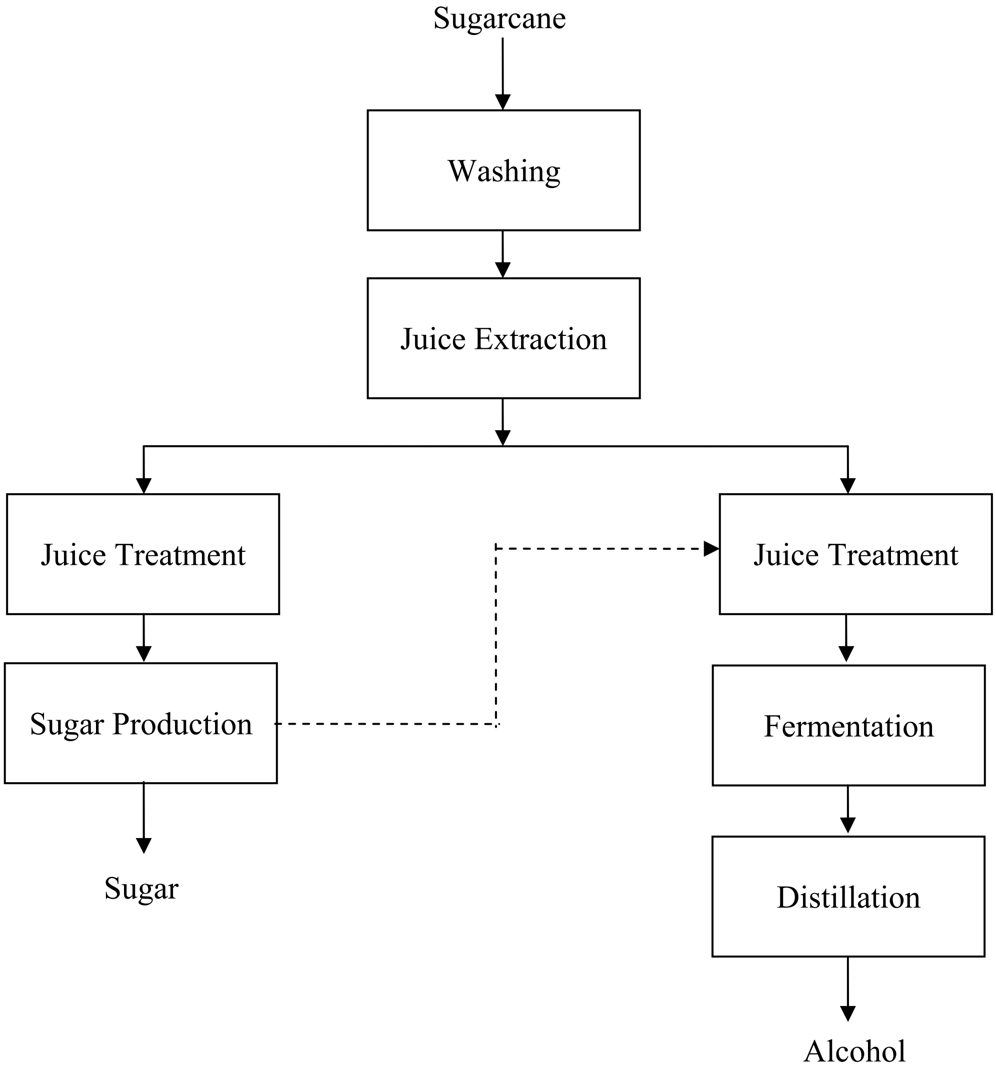


Figure 3



FIGURES CAPTIONS

Figure 1: The Brazilian Regions [1]
Figure 2: North-east States sugarcane cultivated area in km² in 2000 [8].
Figure 3: Sugarcane-based sugar mill production processes [40].

TABLES

Table 1

Elements	References				
	[53]	[54]	[56]	[57]	Average
Carbon (C)	44.40	44.10	48.64	51.70	47.21
Hydrogen (H_2)	6.50	5.26	5.87	6.30	5.98
Oxygen (O_2)	42.00	44.4	42.82	42.00	42.81
Nitrogen (N_2)	0.20	--	0.16	--	0.18
Ash	7.00	4.20	2.44	3.4	4.26

Table 2

Elements	*phyllostachys nigra*	*phyllostachys bambusoides*	*phyllostachys bissetii*	*bambusa vulgaris*
Carbon (C)	51.19	51.84	51.70	51.58
Hydrogen (H_2)	5.29	5.18	5.00	5.16
Oxygen (O_2)	42.12	41.33	42.11	41.85
Nitrogen (N_2)	0.29	0.60	0.30	0.40
Chlorine (Cl)	0.14	0.06	0.03	0.08
Sulphur (S)	0.03	0.05	0.03	0.04
Ash	0.87	0.84	0.78	0.11

TABLE CAPTIONS

Table 1: Oven-dry bagasse ultimate analysis. Values are expressed in % by weight.
Table 2: Ultimate analysis (% by weight) for the studied bamboo species [60-64].

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2004-01-01T00:00:00Z

Pedro Anselmo Filho and Ossama Badr, Biomass resources for energy in North-Eastern Brazil, Applied Energy, Volume 77, Issue 1, January 2004, Pages 51-67.

http://dx.doi.org/10.1016/S0306-2619(03)00095-3