PROSPECTS FOR SUSTAINABLE, UTILITY-SCALE BIOMASS-BASED ELECTRICITY SUPPLY IN NORTHEAST BRAZIL

A.E. Carpentieri[a]
E.D. Larson[b]
J. Woods[c]

PU/CEES Report No. 270

July 1992

Center for Energy and Environmental Studies
School of Engineering and Applied Science
Princeton University, Princeton, NJ, USA

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[a] Division of Alternative Energy Sources, Hydroelectric Company of Sao Francisco (CHESF), Recife, Pernambuco, Brazil

[b] Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, USA

[c] Division of Biosphere Sciences, King's College, London, United Kingdom

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A.E. Carpentieri
Division of Alternative Energy Sources
Hydroelectric Company of Sao Francisco
Recife, Pernambuco, Brazil

E.D. Larson
Center for Energy and Environmental Studies
Princeton University
Princeton, New Jersey, USA

J. Woods
Division of Biosphere Sciences
King's College
London, United Kingdom

ABSTRACT

We present a detailed technical and economic assessment of the potential for establishing a wide-spread, biomass-based electric power generating system in the semi-arid Northeast region of Brazil. Hydroelectric resources in the Northeast will be exhausted about the year 2000. Unless viable alternatives can be found, relatively high-cost hydroelectric resources in the environmentally-sensitive North (Amazon) region will be tapped after 2000 to meet electricity demands in the Northeast. The Division of Alternative Energy Sources of the Hydroelectric Company of Sao Francisco (CHESF), the federally-owned utility responsible for generation and transmission of bulk electricity in the Northeast initiated studies in 1982 to quantify the potential of using for electricity biomass residues of sugarcane production/ processing and *Eucalyptus* trees grown on energy plantations established on currently unforested lands. The analysis here builds on these studies, and includes the possibility of converting biomass into electricity using advanced gas-turbine technologies that are now the focus of commercial demonstration projects in Brazil and elsewhere. Our analysis indicates that existing sugarcane residues and future potential production of plantation *Eucalyptus* could be used to generate annually up to 41 TWh and 1400 TWh of electricity, respectively, compared to CHESF's present annual generation of about 30 TWh. The cost of most of the biomass-derived electricity would be under 4.5 cents/kWh, which compares favorably with marginal costs projected for hydroelectric projects in the Amazon region. Expansion of the CHESF system based on biomass rather than hydropower would also bring social benefits, including greater job creation and lower investment per job created.

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1. Introduction

Biomass is of growing interest worldwide as an energy source because of potential local economic and ecological benefits, as well as potential global environmental benefits arising from its use. If biomass is grown at the same average rate at which it is consumed for energy, little or no net atmospheric emissions of carbon dioxide result. To the extent that fossil fuels are replaced, there would be net reductions in carbon dioxide emissions (Hall, et al., 1991). At the local level, if the economics are favorable, biomass is attractive because it is an indigenous energy source. Biomass is of particular interest in developing countries because growing it is a rural, labor-intensive activity. Jobs might be created in rural areas, helping to stem urban migration. Conversion of biomass to more convenient energy forms like electricity might help spur rural industrialization more generally.

The large-scale commercialization of biomass energy also carries the risk that cutting of existing forests would be accelerated. Thus, an important component of future biomass energy programs will be the production of biomass in ecologically sustainable ways. Dedicated energy plantations are one potential long-term sustainable source of biomass. Globally, the potential plantation-biomass resources are huge. One analysis (Hall et al., 1992) indicates that if plantations were established on a total amount of land equivalent to 10% of the area now in forests/woodlands, cropland, and permanent pasture, the annual biomass energy production would be larger than present global consumption of all commercial fuels (oil, gas, coal, hydro, and nuclear energy). In developing countries, the annual biomass production would equal the present level of commercial energy use. In developing countries, already-deforested or otherwise degraded lands would be attractive candidates for the establishment of plantations. In fact, plantations might provide a means for stabilizing degradation and restoring the lands to productive use.

The cost of biomass from plantations will be higher than biomass cut from natural forests or residues produced as by-products of industrial or agricultural processes. Thus, the technologies for converting raw biomass into more convenient energy forms such as electricity or liquid fuels, must have lower capital costs and/or higher efficiencies than traditional biomass conversion technologies (Larson, 1991). In the case of electricity production, the focus of this paper, the state-of-the-art technology is the boiler/steam-turbine.

Biomass-based power production based on advanced gas turbine technologies, which are now under active commercial development, promises both lower cost and higher efficiency (Larson, et al, 1989; Williams and Larson, 1992).

We present here a detailed assessment of the potential for establishing a wide-spread biomass/gas turbine-based electricity industry in the largely semi-arid Northeast region of Brazil. We draw on studies initiated in 1982 in the Division of Alternative Energy Sources of the Hydroelectric Company of Sao Francisco (CHESF), the federally-owned utility responsible for production and transmission of bulk electricty in the Northeast. The CHESF studies focussed on understanding the potential for establishing tree plantations in its service territory (in areas remote from the rain forests of Amazonia -- Fig. 1), and on alternative technologies for converting biomass into electricity (CHESF, 1985; CHESF, 1987, CHESF, 1989; CHESF, 1990; Carpentieri, 1991; CHESF, 1991a).

2. Background

2.1. The Northeast

Table 1 gives comparative characteristics of the five geographical regions of Brazil. The land-rich Northeast has a population density that is the lowest among the three most heavily populated regions of the country. The fraction of the population living in urban areas is relatively lower than in most of Brazil, but the urban fraction is projected to grow considerably faster than population overall. Per-capita income in the Northeast is lower than for any other region (about half the average for all of Brazil), reflecting the heavy agricultural dependence of the economy. Nearly half of all agricultural jobs in Brazil are found in the Northeast. The average employment per unit of cultivated area, which is higher for the Northeast than any other region, reflects a relatively lower level of agricultural mechanization in this region.

2.2. Electricity

Electricity consumption per capita in Brazil averaged 1372 kWh in 1990, about 2.5 times the average for developing countries and one-fifth the average for industrialized countries. Electricity consumption per-capita in the Northeast was the lowest among Brazil's

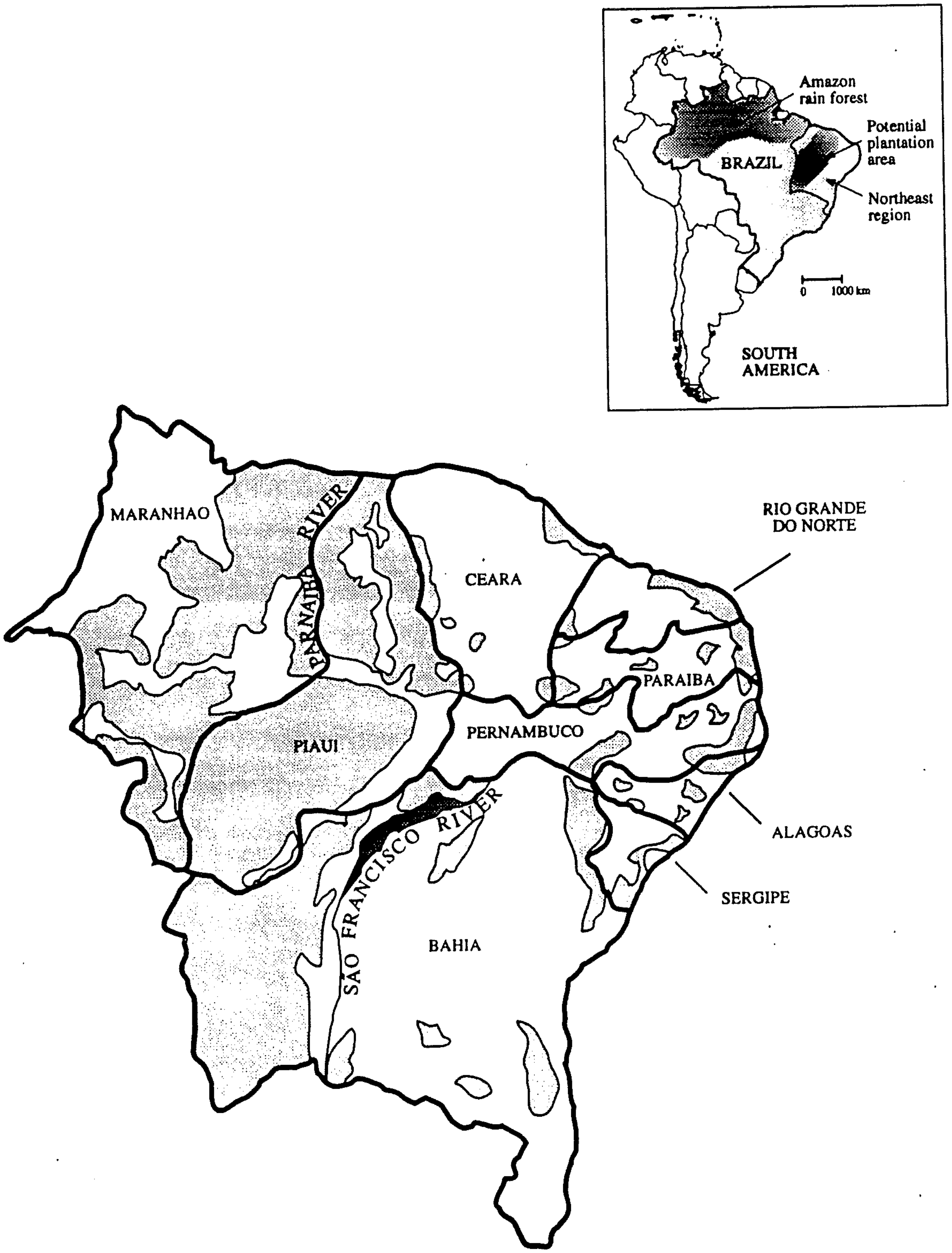

Figure 1. The large map shows the location of areas identified by CHESF as available and suitable for plantation establishment in the Northeast region of Brazil (shaded areas). The inset shows the location of the Northeast within South America and relative to the Amazon rain forest. Note the scale for the inset map.

Table 1. Regional characteristics and indicators for Brazil.[a]

Region	Total Area (km^2)	1990 Population Total (1000)	1990 Population Urban (%)	1990 Pop. density (p/km^2)	Population growth, 1990 -2000, %/yr Total	Population growth, 1990 -2000, %/yr Urban	1988 income per-cap. ($/p)	1985 Agricultural indicators[b] Area (km^2)	1985 Agricultural indicators[b] Jobs (1000)	1985 Agricultural indicators[b] Jobs/ km^2
North	3851560	8893	56	2.3	2.60	3.44	1335	448844	2230	5.0
Northeast	1556001	42822	58	27.5	1.60	2.72	1042	919881	10375	11.3
Southeast	924266	65559	88	70.9	1.77	2.09	3164	736147	47401	6.4
South	575316	22762	74	39.6	1.64	2.49	2473	48711	44632	9.2
Center-West	1604852	10332	78	6.4	2.22	2.91	1826	1170863	14652	1.3
BRAZIL	8511966	150368	75	17.7	1.79	2.41	2250	3762866	232735	6.2

(a) Unless otherwise indicated, data are from (IBGE, 1991).

(b) From (IBGE, 1985).

Table 2. Characteristics of the Brazilian electricity sector in 1990.[a]

Region	Total consumption per-capita (kWh/cap)	Installed hydro-electric capacity (MW)	Installed hydro-electric capacity (% total)	Hydroelectric production (GWh)	Hydroelectric production (% total)	Estimated total hydroelectric resource (MW)	Estimated total hydroelectric resource (% installed)
North	986	3979	83.6	17518	91.1	97800	4
Northeast	731	7217	91.4	27753	99.9	15500	47
Southeast	1958	33207[b]	94.4	147079[c]	95.3	56200[d]	60
South	1240	5586	82.9	30797	91.2	43500	13
Center-West	844	545	84.4	3230	94.1	d	d
BRAZIL	1372	50,534	91.5	226377	95.8	213000	24

(a) Sources: Eletrobras and (IBGE, 1991).

(b) Including 11200 MW on-line at Itaipu.

(c) Including 51,060 GWh from Itaipu.

(d) The resource capacity in the Center-West region is included in the Southeast region's total.

five regions -- about half the national average and one-third the average of the heavily-industrialized Southeast (Table 2). Growth in electricity consumption in the Northeast in the 1980s paralleled that in Brazil as a whole, averaging about 5% per year. Projected growth rates for the Northeast are in the range of 4.7 to 7.0% per year from 1991 to 2015 (CHESF, 1991b). The projected capital investment needed in new power plants (all hydroelectric) to meet this demand growth is estimated to be in excess of $25 billion.[1] This rate of investment -- about $1 billion per year -- is 7 times greater than the average rate of investment since 1954, when the first CHESF hydroelectric plant came on line.

Over 95% of all electricity produced in Brazil and essentially 100% produced in the Northeast is hydroelectric. The installed hydroelectric capacity nationally in 1990 was some 50 GW, or about one-quarter of the estimated total resource potential (Table 2). The largest untapped hydropower resources are in the environmentally-sensitive North region and associated with the Amazon river and its tributaries. The Southeast and Northeast have tapped the largest fractions of their hydroelectric potential, 60% and 47%, respectively. The development of essentially all remaining hydroelectric potential in the Northeast is planned by the year 2005, with investment costs projected to increase as less favorable sites are developed (Fig. 2, top). The marginal cost of electricity production is expected to rise correspondingly (Fig. 2, bottom).

The prospect of rising costs of hydroelectricity and of exhausting the hydroelectric potential in the Northeast were recognized at CHESF around 1980. With no indigenous fossil energy, CHESF is considering expanding electricity supply to the Northeast by importing electricity from new hydroelectric projects that would be located in the Amazon River basin. Such an alternative would raise average electricity costs, as discussed later, and would be environmentally controversial. It would also involve little direct long-term investment or job creation in the Northeast, two social objectives which a public utility like CHESF seeks to achieve through its expansion efforts. To identify more attractive electricity supply

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[1] All costs in this paper are expressed in 1988 US dollars. Conversions from Cruzeiros to dollars have been made at exchange rates prevailing at the time to which the Cruzeiro costs correspond, and the US GNP deflator (Council of Economic Advisors, 1992) has been applied to convert the dollar values into constant 1988 $.

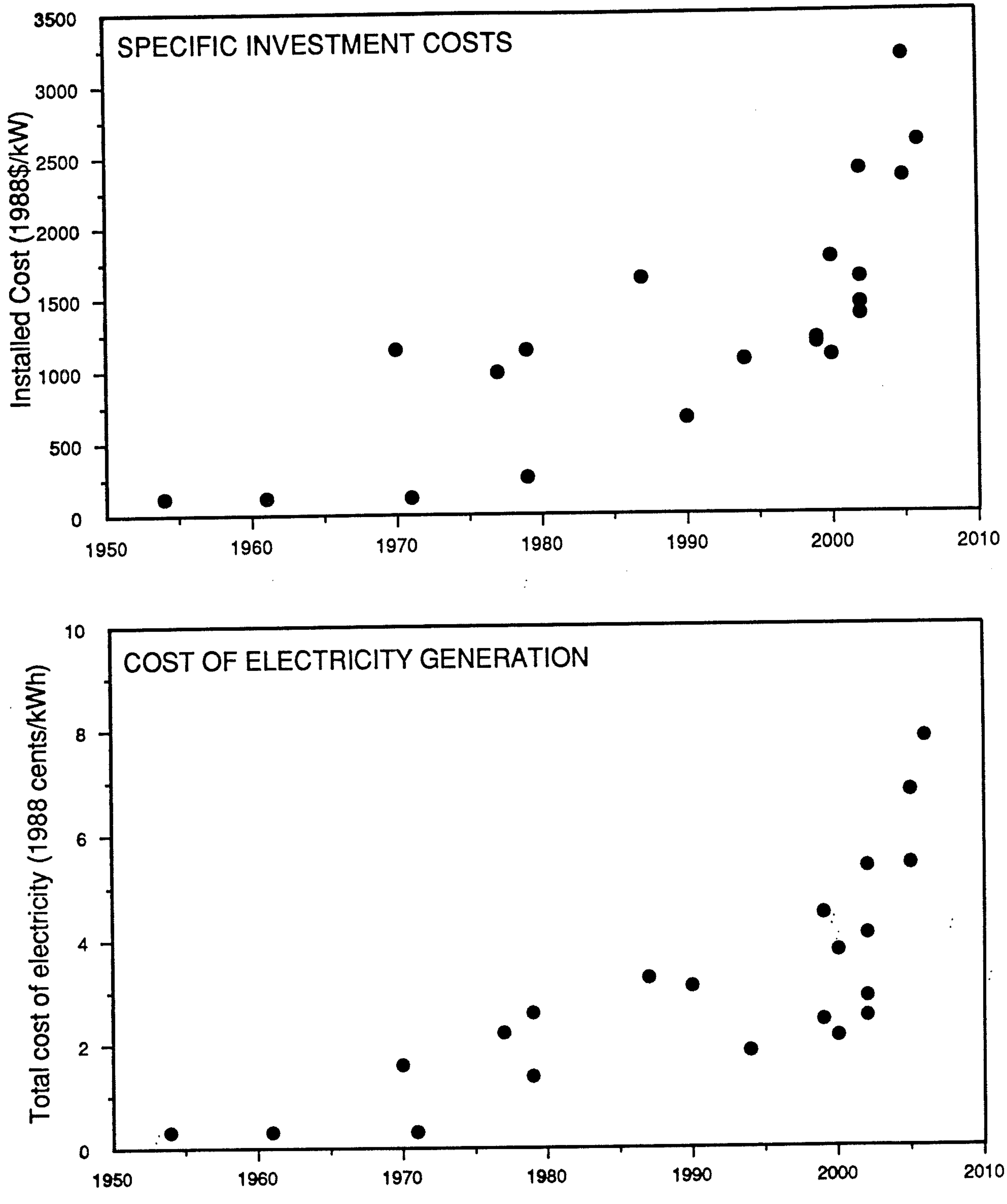

Figure 2. Cost characteristics of the hydroelectric power plants in the service territory of the Hydroelectric Company of Sao Francisco. Each point represents an individual plant currently on the CHESF system or projected for commissioning. The upper graph shows investment costs per installed kW (including interest during construction). The lower graph shows total levelized costs of electricity production, including capital and operating costs.

alternatives, CHESF initiated a research and development effort in 1980. A major part of this effort has involved assessing the prospects for widespread production of electricity from biomass in the Northeast, as discussed in this report.

2.3. Biomass Use Today

Globally, biomass accounts for about 15% of all primary energy use (Hall et al., 1992). In industrialized countries, it represents about 3% of energy use. In developing countries, it averages 38% of energy use. In Brazil, biomass accounts for 25% to 30% of energy use. In most developing countries, the collection and use of biomass is largely unorganized and non-commercial, with most biomass being used in cook stoves. In contrast, the character of bioenergy use in Brazil has been changing rapidly since the mid-1970s toward large-scale, commercial processing and use (Fig. 3). The two most important sources of biomass energy in Brazil today are wood fuel and sugarcane.

Some 50% to 60% of all bioenergy is wood fuel, part of which is used in traditional ways -- for cooking or for small-scale industry. The majority of wood fuel is now converted in organized, large-scale commercial operations into more convenient forms: charcoal (for iron-ore reduction and heating) and steam and electricity (for on-site use in cement mills, pulp & paper mills, food processing, and other large-scale industries).

Industrial-scale use of charcoal has been ongoing since the 1950s. Plantation production of charcoal feedstocks was encouraged by the 1965 National Forestry Act, which provided considerable tax incentives for plantation establishment (Betters et al., 1991). The rate of charcoal production accelerated with the oil-price shocks of the 1970s (Fig. 3). Private-sector plantation feedstock production also accelerated in this time period, as the charcoal-using industries realized that continued exploitation of natural forests would soon strip Brazil's natural forests. Plantation establishment efforts have been quite successful, with about 35% of all charcoal now being derived from plantations (ABRACAVE, 1992). Over 30% of all pig iron and about 24% of steel are now made using charcoal. Large-scale plantations also began to be developed by the pulp and paper industry in the mid-1970s. This industry now derives all its feedstock from plantations. Estimates of the present plantation area in Brazil range from about 4 million hectares (Bazett, 1992) to over 6 million hectares

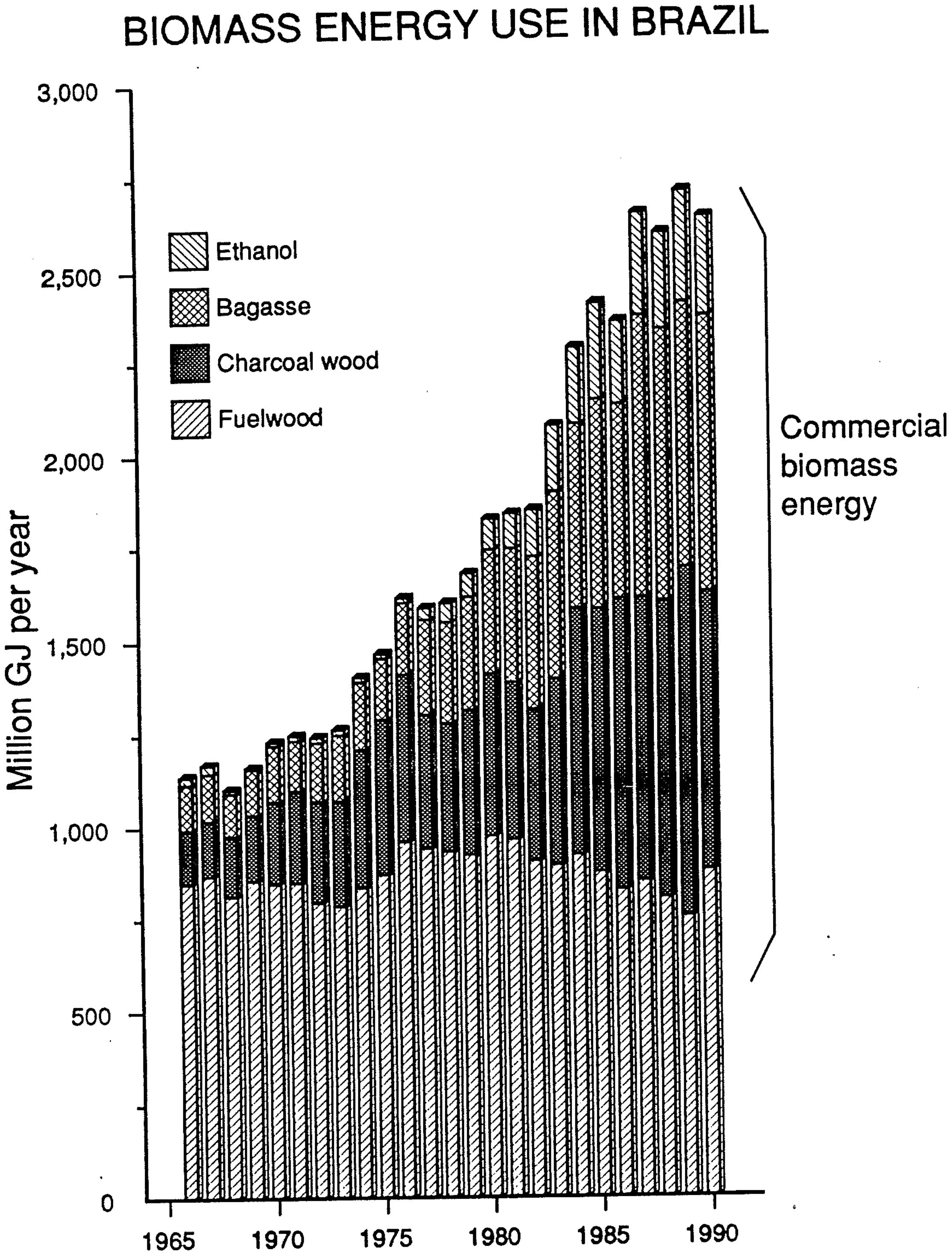

Figure 3. Evolution of biomass energy use in Brazil since 1965. Note that essentially all growth in bioenergy consumption during this period has come in large-scale industrial uses: all bagasse for industrial-sector combined heat and electricity production, much of the charcoal for iron-ore reduction in the steel industry, all of the ethanol for transport vehicle use, and some fuelwood. Sources: (IBGE, 1977 and 81; ABRACAVE, 1991 and 1992).

(de Jesus, 1990).[2]

The use of bagasse (the fiber by-product of sugarcane crushing) has grown in parallel with the expansion in sugarcane production that has been ongoing since the Brazilian fuel alcohol program was initiated in 1975 (Fig. 3). Land use has not grown as rapidly as sugarcane production, however, as production per hectare has increased by over 30% since the mid-1970s. Further gains in yield are anticipated. Another potential biomass energy resource from sugarcane are the tops and leaves of the plant, which today are commonly burned or left on the field. Trial collection and use for energy of tops and leaves are ongoing in several countries (Howe and Sreesangkom, 1990). There is growing interest in the Brazilian sugarcane industry in using tops and leaves to produce electricity, particularly since regulations went into effect in mid-1992 in the state of Sao Paulo (the largest cane producing state) guaranteeing that electricity generated privately from cane residues would be purchased by utilities at the utilities' marginal cost of production.

The overall impact of biomass use in Brazil has been mixed, as is the case with most energy sources. There have been some negative environmental and institutional impacts. For example, the majority of wood fuel is still being cut from natural forests, contributing to deforestation, soil erosion, siltation of rivers, and other environmental problems. The cutting of natural wood has had a particularly devastating effect on the Northeast region, where essentially all wood fuel still comes from natural forests. Natural forests now cover less than 4% of the land area of the Northeast. In addition, at industrial facilities where fuel ethanol is made from sugarcane, the improper disposal of stillage (waste water) from distilleries has had detrimental environmental impacts. An example of an institutional problem has been the suppression of entrepreneurial spirit in the cane-processing industries as a result of subsidies introduced in the mid-1970s (and eliminated about a decade later) that were successful in encouraging the establishment of the sugarcane-ethanol industry.

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[2] The lower estimate includes only industrial plantations. The higher estimate also includes reforested areas not used for industrial purposes. (For example, there are unharvested areas that were planted to capture tax benefits.) The estimates of the amount of non-industrial reforested area are uncertain, because reforestation has not been fully successful in all areas planted.

While there have been negative impacts of bioenergy development in Brazil, there have also been clear benefits. Foremost among these has been the creation of an estimated 200,000 jobs at wood plantations and 600,000 jobs in the sugar industry. Also, the wood plantation and sugarcane industries are recognized as world leaders. Each year the area planted with wood has grown, and new understanding and new technologies are being developed for utilizing biomass in environmentally acceptable ways. For example, the recuperation of environmentally damaging tars in the production of charcoal is now practiced by most companies, and stillage from ethanol production has been developed as a fertilizer in many areas.

Despite the mixed success of bioenergy to date, attitudes about biomass among private and public sector decision makers are changing as a result of factors such as better scientific understanding of environmental impacts, new government-imposed controls over industrial activities, new enforcement powers given to environmental agencies, pressures to remove subsidies of all types, and the practical fact that little natural wood is left at reasonable distances. Given these changing attitudes, the past experience with organized industrial-scale production and use of biomass, the development of new scientific understanding and new technologies, and the potential social benefits of biomass energy development, the prospects for enlarging the role of biomass energy in Brazil in environmentally-compatible ways are encouraging.

2.4. Brazilian Biomass Plantation Technology

As noted, Brazil has between 4 and 6 million hectares of wood plantations today, the majority of which provide feedstocks for Brazilian steel and pulp producers whose products are competitive with the best products anywhere in the world. Part of Brazilian industry's competitive advantage lies in the low cost of its plantation wood feedstocks. In efforts to maintain this competitive advantage, Brazilian forestry companies have invested heavily over the past three decades or so in improving biomass plantation technology (Campinhos and Ikemori, 1989; Betters et al, 1991). The result has been a dramatic evolution in plantation technology during the past 15 to 20 years. Improvements in soil preparation, planting, and cultivation methods, in pest, disease, and fire control, and in species selection and propagation, including the application of biotechnology, have all contributed to significant increases in average yields. Harvesting and transportation techniques have also been refined, contributing to signficant cost reductions over this period. In parallel with these developments, a large and expert research infrastructure has developed, out of which continued improvements in plantation technology can be expected.[3]

3. Biomass Production Potential for Electricity Generation in the Northeast

The Northeast region has three types of biomass resources that might be utilized for electricity production: sugarcane residues, plantation trees, and residues of other agricultural products. The first two of these are the most promising for large-scale use because of the organized production associated with them today and their history of association with energy production in Brazil. Residues of other agricultural products are also a potential energy source, the amount generated annually (114 PJ/year, Table 3) being equivalent to about 10% of total primary energy consumption in the Northeast today. Crop residues are generally widely dispersed and have not traditionally been used for energy, however, which makes their large-scale organized use more challenging. We do not consider them in this paper, but note that they could be locally significant.

3.1. Sugarcane Residues

Sugarcane has been growing in Brazil for centuries. The use of bagasse as an energy source to meet sugar factory energy demands dates to the beginning of the 19th century. Bagasse has continued to be used in the 20th century in boilers to raise steam for on-site process use and for electricity production to meet on-site needs (Goldemberg, et al., 1992). More recently, bagasse has been receiving attention as an energy resource for producing electricity in excess of on-site needs. This new view of bagasse has begun to modify the

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[3] Key research institutes include: IPEF (Instituto de Pesquisas Florestais), EMBRAPA (Empresa Brasileira de Pesqusa Agropecuaria), CPATSA (Centro de Pesquisa Agropecuaria para o Tropico Semi-Arido, belonging to EMBRAPA), ESALQ (Escola Superior de Agricultura Luiz de Queiroz at the University of Sao Paulo, Campus de Piracicaba), and the School of Forestry at the University of Vicosa (state of Minas Gerais). Most companies with large plantation activities also maintain their own research efforts.

Table 3. Production of crops[a] and estimated energy content[b] of associated residues in Northeast Brazil in 1990.

State	*Maize*		*Rice*		*Oranges*		*Cassava*		*Cotton*		*Beans*		*Other*[c]	*Total*
	(10^3 t)	(10^6 GJ)	(10^3 t)	(10^6 GJ)	(10^3 t)	(10^6 GJ)	(10^3 t)	(10^6 GJ)	(10^3 t)	(10^6 GJ)	(10^3 t)	(10^6 GJ)	(10^6 GJ)	(10^6 GJ)
Alagoas	39.4	1.2	26.5	0.3	28.5	0.1	161.8	0.1	2.7	0.1	30.7	0.1	0.1	2.0
Bahia	281.5	8.5	84.5	1.1	2066.1	5.0	4352.6	3.3	114.2	4.1	200.5	0.8	3.7	26.5
Ceara	236.0	7.1	146.2	1.9	86.4	0.2	980.7	0.8	39.0	1.4	119.2	0.5	0.0	11.9
Maranhao	334.2	10.0	1091.6	13.9	286.8	0.7	1820.8	1.4	0.5	0.0	49.5	0.2	0.2	26.4
Paraiba	156.8	4.7	25.8	0.3	117.1	0.3	436.1	0.3	16.7	0.6	103.9	0.4	0.0	6.6
Piaui	363.5	10.9	347.9	4.4	178.9	0.4	2012.5	1.5	5.7	0.2	82.7	0.3	0.0	17.7
Pernambuco	198.7	6.0	34.1	0.4	147.5	0.4	1165.0	0.9	6.7	0.2	89.3	0.4	0.0	8.1
R.G. de Norte	51.6	1.6	7.2	0.1	21.7	0.1	472.2	0.4	10.9	0.4	56.9	0.2	0.0	2.8
Sergipe	81.2	2.4	22.6	0.3	3529.8	8.5	379.7	0.3	1.5	0.1	19.0	0.1	0.0	11.7
Total NE	1743.0	52.3	1786.4	22.8	6462.7	15.6	11781.3	9.0	197.9	7.1	751.7	3.1	4.0	113.9

(a) From (IBGE, 1991).

(b) Based on residue ratios (tonnes of residues per tonne of crop), higher heating value energy contents of the residues (GJ per tonne) as follows. Maize: 2.1, 18; rice: 1.03, 12; Citrus: 0.47, 6; Cassava: 0.15, 10; Cotton: 3.5, 12; and Beans: 0.8, 12; Other includes castor oil: 0.6, 6; coffee: 0.2, 15; and soybeans: 0.56, 10. Source: (Strehler and Stutzle, 1987).

(c) Other includes castor oil, coffee, and soybeans.

profile of the sugarcane industries. For example, a few sugarcane processing facilities are now selling small quantities of excess electricity to utilities.

More profound modifications of the industry are likely in the future, aimed at improving the industry's overall competitiveness (Copersucar, 1989; Goldemberg et al, 1992). A sugar mill or alcohol distillery of the future is likely to be seen not only as a producer of sugar or alcohol, but also as an electricity exporter. The movement of the industry in this direction will be encouraged by the development of advanced technologies for converting biomass to electricity more efficiently and at less cost than is the case today (see Section 4). There are also likely to be efforts made to utilize the tops and leaves of the sugarcane plant to the extent that can be managed sustainably. (Presently, cane fields in Brazil are burned before harvest, which facilitates harvesting of the sugar-laden stalks. The tops of the stalks and remaining unburned leaves are left or burned on the field after harvest.) Furthermore, cane yields per hectare are likely to increase in the future as improved varieties and better agronomic practices are developed. Large gains are probably possible in both sugar and bagasse yields per hectare if emphasis is placed on increasing biomass productivity, rather than sugar alone (Alexander, 1985).

To estimate the potential biomass energy from sugarcane that could be utilized for electricity generation in the Northeast of Brazil, we consider three alternative scenarios for the sugarcane industry, each characterized by a different level of agronomic development: present, near-future (NF), and advanced future (AF). The NF and AF scenarios are intended to represent plausible pictures of the industry in the late 1990s and in the post-2000 time frame, respectively. For each scenario, detailed estimates of technical, economic, energetic, environmental and social characteristics of five phases (planting, cultivation, harvesting, transporting and processing) associated with extracting biomass energy from sugarcane were developed (Carpentieri, 1991).

Table 4 summarizes the production characteristics of the three scenarios. Cane yields per hectare per year are assumed to grow modestly in the 1990s, with larger gains anticipated within a decade or so. In addition to increases in bagasse energy availability in the future resulting from gains in overall cane productivity, the other major source of additional biomass

Table 4. Average sugarcane industry production characteristics for present, near future and advanced future scenarios.[a]

SCENARIO --->	PRESENT	NEAR FUTURE	ADVANCED FUTURE
Rotation time (years)	5	4	4
Cuts/rotation	4	3	3
Cane production			
tc/ha/cut	65	73	95
tc/ha/year	52.0	54.8	71.3
Residue production (50% moisture content)			
Bagasse (t/tc)	0.295	0.295	0.295
Tops & leaves (t/tc)			
total production[b]	0.46	0.46	0.46
total recoverable[c]	---	0.25	0.25
assumed recovered[d]	---	0.18	0.23

(a) Except for the numbers relating to tops and leaves, this table is based on data and analysis from (Copersucar, 1989).

(b) From (Alexander, 1985).

(c) Assuming that only the green top of the cane and attached leaves can be recovered. Detached leaves, which account for the balance, are assumed to be unrecoverable.

(d) The near future case is based on recovery rates achieved in trials in Thailand (Howe and Sreesangkom, 1990). In the advanced future case, the recovery rate is assumed to improve to 92% of the recoverable total.

are the tops and leaves of the cane plants. In the post-2000 time frame, tops and leaves are expected to be able to provide nearly as much biomass energy as the bagasse (Table 4). Despite their large energy contribution, the tops and leaves used for energy will account for only half of the total tops and leaves produced; the balance being left on the fields to return nutrients and organic matter to the soil.

Table 5 summarizes the biomass energy production potential from sugarcane in the Northeast, assuming the same amount of land planted with cane as in 1989. Present biomass production (all bagasse) amounts to some 174 PJ/year. In the next decade or so (NF

Table 5. State-by-state biomass energy production potential from sugarcane in Northeast Brazil, assuming the same area is planted with sugarcane as in 1989.[a]

	------- **PRESENT**[b] -------			----- **NEAR FUTURE** -----			---- **ADV. FUTURE** ----		
State	*Planted Area* (10^3 ha)	*Cane yield* (tc/ha/yr)	*Bagasse*[c] (10^6 GJ)	*Cane yield*[d] (tc/ha/yr)	*Tops & Leaves* (10^6 GJ/yr)	*Total Residues*[c]	*Cane yield*[d] (tc/ha/yr)	*Tops & Leaves* (10^6 GJ/yr)	*Total Res.*[c]
Alagoas	489	46.7	57.0	49.2	35.9	96.0	64.0	59.8	137.9
Bahia	81	44.9	9.13	47.3	5.75	15.4	61.6	9.57	22.1
Ceara	64	44.8	7.13	47.2	4.49	12.0	61.4	7.46	17.3
Maranhao	36	54.8	4.95	57.8	3.12	8.30	75.1	5.18	11.9
Paraiba	159	54.5	21.6	57.4	13.6	36.4	74.7	22.6	52.2
Pernambuco	445	54.1	60.2	57.0	1.21	3.24	74.2	2.02	4.7
Piaui	15	52.4	1.92	55.2	37.9	101.4	71.8	63.1	145.6
R.G. de Norte	57	50.4	7.17	53.1	4.52	12.1	69.1	7.51	17.4
Sergipe	33	62.2	5.18	65.5	3.27	8.73	85.3	5.43	12.5
TOTALS	1379	50.6	174.3	53.3	109.8	304.0	69.4	182.6	421.8

(a) See Table 4 for cane and residue production characteristics associated with each scenario.

(b) Presently planted area and average yields are for 1989 (IBGE, 1990).

(c) Assuming bagasse and tops/leaves recovery rates as in Table 4. The higher heating value of bagasse with a 50% moisture content is assumed to be 8.47 GJ/tonne; that for tops and leaves with a 50% moisture content is assumed to be 8.3 GJ/tonne (Carpentieri, 1991).

(d) In the near future and advanced future, yields are assumed to be increased by 5.4% and 37%, respectively, the percentage increases shown in Table 4.

scenario), the bioenergy available from sugarcane could be increased by up to 75% over the current level through use of the tops and leaves. In the longer term (AF scenario), bioenergy from sugarcane might reach 420 PJ/yr, or over twice the current level.

A key social aspect of the sugarcane industry is the large number of people it currently employs. In the Northeast alone, it accounts for an estimated 37,000 permanent jobs and 235,000 seasonal jobs. While the number of jobs provided is large, the large seasonal component is problematic. The use of tops and leaves for energy during the off-season may provide an opportunity to reduce the seasonality of employment. In the NF and AF scenarios we present here, total permanent jobs would increase by a factor of about six due to the additional labor needed in the off-season to bale and transport tops and leaves to the electricity generating plant (Table 6). A conceivable alternative would be that baling and transport to a storage site are undertaken during the milling season in parallel with the harvesting of the cane. In this case, the seasonal employment problem would be greatly exacerbated. Thus, in developing strategies for using tops and leaves for energy, it will be important to take into account the effect on seasonal labor requirements.

3.2. Energy Plantations

3.2.1. Potential production

Having a population density that is the lowest among the three most populated regions in Brazil and occupying 18% of the area of Brazil (Table 1), or nearly 10% of South America, the Northeast region counts land as one of its most valuable natural resources. To evaluate the potential for plantation wood supply for energy in the Northeast, CHESF undertook a major biogeoclimatic assessment of all land in the Northeast.

CHESF completed the first three-year long phase of its study in 1985 (CHESF, 1985), with a follow-on survey completed in 1990 (CHESF, 1990). The CHESF efforts were considered pioneering for the Northeast, as well as for Brazil, as they were the first efforts undertaken to establish in detail the energy plantation potential of any region in Brazil. The studies mapped soil and climate throughout the Northeast and collected and analyzed yield, cost, and other data from various commercial and research efforts focussed on the Northeast region over the last 20 years. They drew on results of 66 experimental plantations,[4] and on data from plantations operated commercially by several major companies.[5]

The CHESF studies recognized the potential conflict between the use of large areas of land for energy plantations and for other uses, in particular food production. For this reason,

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[4] The Centro de Pesquisa Agropecuaria para o Tropico Semi-Arido (CPATSA), which operates under the Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA), maintains an extensive database on experimental plantation efforts.

[5] Two of the companies were from the state of Minas Gerais, which borders the Northeast: the Companhia Agro Florestal Santa Barbara (CAF) and Acesita Florestal, the charcoal producing company associated with Acesita Steel. Two others were from the Northeast: Copene Energetica (COPENER), a major forestry company in Bahia state and the daughter company of Companhia Petroquimica do Nordeste--COPENE, and Cimento Nassau, a large cement company in Ceara state.

Table 6. Sugarcane-related milling-season (on) and non-milling season (off) labor requirements and employment potential by state in the Northeast for present, near future and advanced future scenarios.[a]

SCENARIO --->	**PRESENT**		**NEAR FUTURE**		**ADVANCED FUTURE**	
Jobs per km^2	*On*	*Off*	*On*	*Off*	*On*	*Off*
Sugarcane[b]						
Planting	1.51	--	1.60	--	1.44	--
Growing	5.89	--	5.69	--	5.92	--
Harvest	7.88	--	7.97	--	4.15	--
Transport	1.83	--	1.83	--	2.19	--
Processing	2.65	2.65	2.52	2.52	2.78	2.78
Subtotal	**19.76**	**2.65**	**19.61**	**2.52**	**16.48**	**2.78**
Tops and leaves[c]						
Baling	--	--	--	4.3	--	5.1
Transport	--	--	--	9.7	--	7.4
Subtotal	**--**	**--**	**--**	**14.0**	**--**	**12.5**
TOTAL	**19.8**	**2.65**	**19.6**	**16.5**	**16.5**	**15.3**
State	***Total Potential Jobs*** (10^3)[d]					
Alagoas	96.6	13.0	95.8	80.9	80.5	74.6
Bahia	16.1	2.2	16.0	13.5	13.4	12.5
Ceara	12.6	1.7	12.5	10.5	10.5	9.7
Maranhao	7.1	1.0	7.1	6.0	6.0	5.5
Paraiba	31.4	4.2	31.1	26.3	26.2	24.3
Piaui	2.9	0.4	2.9	2.5	2.4	2.3
Pernambuco	88.0	11.8	87.3	73.7	73.4	68.0
R.G. de Norte	11.3	1.5	11.2	9.5	9.4	8.7
Sergipe	6.6	0.9	6.5	5.5	5.5	5.1
Total Northeast	**272.6**	**36.7**	**270.4**	**228.4**	**227.3**	**210.7**
Total number of jobs **(% seasonal)**	**272.6** **76%**		**270.4** **16%**		**227.3** **7%**	

(a) See Table 4 for cane and residue production characteristics associated with each scenario.

(b) Based on (CHESF, 1987) and on productivity gains indicated in Table 4. See (Carpentieri, 1991).

(c) Preliminary estimates based on (Howe and Sreesangkom, 1990). See (Carpentieri, 1991). Transport during the off-season without first baling would create fewer jobs: 7.14 and 8.40 jobs/km^2 for the Near Future and Advanced Future scenarios, respectively.

(d) Assuming the area planted with sugarcane to be the same as in 1989 (see Table 5).

the CHESF assessments considered only land area judged to be sub-optimal for agriculture. Despite this constraint, the estimated potential land area available for plantations is about 50 million hectares, or about 1/3 of the land area of the Northeast (Fig. 4, top), most of which is contained in three states: Bahia, Maranhao, and Piaui (Fig. 4, lower right). Most of the area falls within a large band flanking either side of the Parnaiba River and in an area to the southwest of the Sao Francisco River (Fig. 1).

The potential plantation areas identified by CHESF are largely unused for any economic purpose today. Much of the land is classified as "cerrados", the primary natural vegetation on which is shrubs. Some of the areas support peculiar ecosystems, and plantation development efforts would need to include detailed environmental studies to identify strategies for maintaining or strengthening these existing ecosystems.

To determine the wood production potential of the available land, CHESF undertook comprehensive state-by-state studies to map the geography, soil characteristics, water drainage patterns, temperatures, precipitation, insolation, elevation and water deficit level in these areas. Five "bioclimatic regions" (BCRs), each defined in terms of average temperature, elevation, precipitation, and water deficit,[6] were identified from these studies (Table 7). Region I provides the best conditions for tree growth and Region V provides the worst. All of the regions are water deficient, which makes them sub-optimal for tree growth relative to some other regions of Brazil. The largest fraction of the potential plantation area in the Northeast falls in BCR III (Fig. 4, lower left). Onto the BCR map, CHESF added a detailed mapping of soil conditions (drainage, slope, rockyness, compaction, pH, organic matter status, etc.). Finally, to estimate yields of wood, CHESF combined its BCR/soil map with data on wood yields from existing plantations falling in similar edaphobioclimatic regimes. Yield data were obtained for both large-scale commercial *Eucalyptus* plantations maintained by pulp, steel, or cement producers (Table 8) and for smaller-scale experimental *Eucalyptus* plantations (Table 9). CHESF analysis indicated that precipitation was by far the most important determinant of yield.

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[6] Water deficit is defined as the difference between the potential evapotranspiration (the amount of water that could theoretically be transpired by plants and evaporated from the soil under the local environmental conditions) and the actual precipitation.

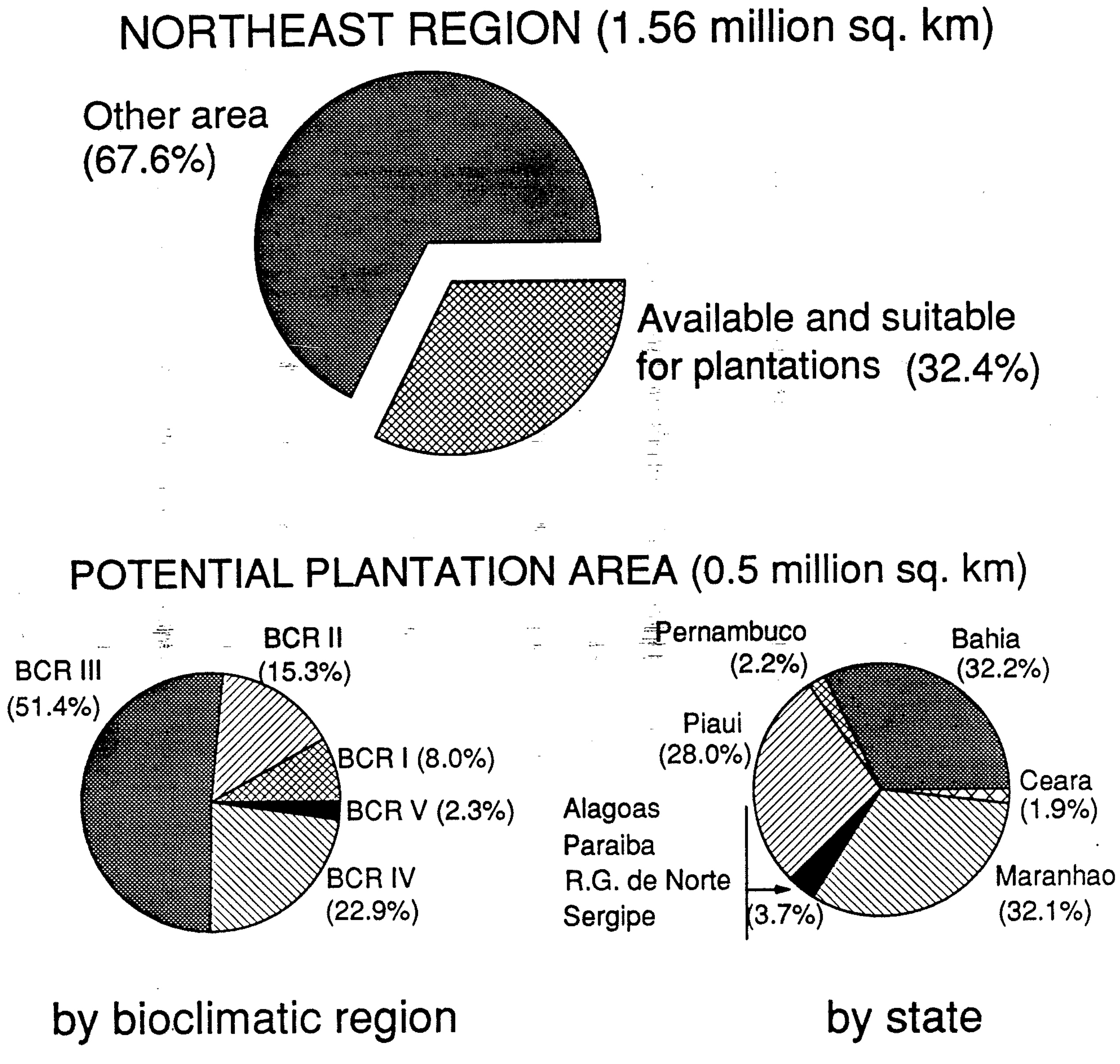

Figure 4. Size and distribution of land judged suitable for biomass plantations in Northeast Brazil. The upper pie shows the fraction of the total area of the Northeast available. The lower right pie shows the distribution of plantation-suitable land by state in the Northeast. (See Table 9.) The lower right pie shows the distribution of the plantation-suitable area by bioclimatic region. (See Table 9.) See Table 7 for definitions of bioclimatic regions.

Table 7. Characteristization of the five bioclimatic regions defined for Northeast Brazil.[a]

	Bioclimatic Region				
	I	*II*	*III*	*IV*	*V*
Average temperature (C)	22-28	24-28	24-28	26-28	24-28
Elevation (meters)	0-700	<900-1000	<700-1000	<700	<600
Precipitation (m/year)	1.5-2.3	1.0-1.7	0.7-1.3	0.5-1.0	0.25-0.6
Water deficit (m/year)[b]	0-0.1	0.05-0.3	0.2-0.6	0.5-1.0	0.8-1.3

(a) The parameter values for each bioclimatic region are not precisely defined. This table shows typical values for the Northeast states of Brazil. Source: (Carpentieri, 1991).

(b) Water deficit is defined as the potential evapotranspiration minus actual precipitation.

To simplify the comprehensive results of the CHESF analysis, we have taken rainfall as the single parameter correlating plantation yields with bioclimatic region. We have taken the average yield of the plantations existing presently in areas receiving a particular level of precipitation and assigned this yield to the BCR receiving a similar level of rainfall.[7] In the case of bioclimatic region I, where yields are expected to be the highest, there were relatively little plantation data on which to draw, so a conservative best estimate of yield was made.[8] In our analysis, bioclimatic regions I through V are estimated to be able to produce an average of 44, 33, 28, 15 and 6 m^3/ha/yr of wood,[9] respectively, over an 18-year cycle, with a weighted average over all BCRs in the Northeast of 26.6 m^3/ha/yr.

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[7] To reflect the likely reduction in productivity associated with going from small, highly managed trials to large commercial plantations, the average yields for the experimental trials (Table 9) were multiplied by 0.75 before averaging for the purpose of estimating yields for bioclimatic regions. The adjusted experimental yields were quite consistent with the yields reported by commercial plantation operators (Carpentieri, 1991).

[8] The average yield in BCR I was taken to be the highest yield on commercial plantations in BCR II.

[9] Unless otherwise noted, m^3 of wood in this paper refers to a solid cubic meter of wood. The equivalent bone-dry weight is assumed to be 0.47 tonnes, having a higher heating value of 20 GJ/tonne. The densities of *Eucalyptus* species vary markedly, ranging, for example, from about 0.35 t/m^3 for *Eucalyptus deglupta* to as high as 0.9 t/m^3 for *Eucalyptus globulus* (Davidson, 1987). The value of 0.47 t/m^3 is representative of the commercially-grown *Eucalyptus* species included in the CHESF yield analysis.

Table 8. Summary of biogeoclimatic data and yields for some commercial *Eucalyptus* plantations in Brazil.[a]

	Location		*Avg. Annual Temp.*	*Annual Rain*	*Alti-tude*	*Soil*		*Time between cuts*	*Peak yield*[d]	*Average yield*[e]
	Lat. (S)	*Long.* (W)	(C)	(mm)	(m)	*type*[b]	*Species*[c]	(yr)	(m^3/ha/yr)	(m^3/ha/yr)
State of Minas Gerais										
CAF										
Bom Despacho	19.35	45.17	22	1375	700	C	*E. grandis*	4.4	50.3	44.0
Carbonita	---	---	21	1025	730	--	*E. cloeziana*	6.0	24.5	21.0
FLORESA										
Vale do Jequitinhona	---	---	21	1025	730	--	*E. pilularis*	4.4	37.6	31.8
Northeast Region										
COPENER										
Inhambupe, Ba	14.47	38.21	24	900	200	S/C	----	6.0	---	30.0
Alahoinhas, Ba	---	---	24	1100	200	S	----	6.0	---	30.0
Entre Rios, Ba	---	---	24	1100	200	C	----	6.0	---	40.0
Cimento Nassau, Ce	7.19	39.17	21	650	900	S	*E. camaldul.*	7.0	---	14.7

(a) Sources: private communications with indicated companies. CAF = Companhia Agricola Florestal Santa Barbara; FLORESA = Florestal Acesita; COPENER = Copene Energetica. All plantations have operated a minumum of 10 years. The CAF Bom Despacho site has operated for approximately 20 years. The areas of plantation maintained by these companies today are as follows (in ha): CAF Bom Despacho, 30000; CAF Carbonita, 25000; FLORESA, 100000; COPENER Inhambupe, 18500; Alahoinhas, 8600; Entre Rios, 13900; Cimento Nassau, 1200.

(b) C = Clay, R = rocky, S = sandy.

(c) All are species within the genus *Eucalyptus*. Spacing of trees are as follows: CAF Bom Despacho: 1.5 x 1; CAF Carbonita: 3 x 1.5, 3x 2, and 2 x 1; Florasa 3 x 2; Copener: 3x2; Cimeno Nassau: 3 x 1.5.

(d) Peak yield refers to the best yield observed in limited areas with the indicated species.

(e) Average yield refers to the yield that would be expected under normal operating conditions at the site.

Table 9. Summary of biogeoclimatic data and yields for trial plantations in Northeast Brazil.[a]

	Location										
Site location	*Lat.* (S)	*Long.* (W)	*Annual Temp.* (C)	*Annual Rain* (mm)	*Altitude* (m)	*Soil type*[b]	*Suitability for forest*[c]	*Best-adapted species*[d]	*Age of experiment* (yr)	*Peak yield*[a] (m^3/ha/yr)	*Average yield*[a] (m^3/ha/yr)
Petrolina, Pe	9.24	40.30	26	500	200-500	S	III	*E. cebra*	8	16.2	11.2
Trindade, Pe	7.45	40.16	26	700	500-1000	C	I/IV	*E. creba*	6	24.2	21.9
Brumado, Ba	14.13	41.40	22	1000	200-500	S/C	I/II	*E. tereticornis*	5	62.5	48.6
Ouricaugas, Ba	12.01	38.37	24	1500	200-500	S/C	II	*E. cloeziana*	9	89.8	59.9
Inhambupe, Ba	11.47	38.21	24	1370	200-500	S/C	II	*E. pellita*	7	39.2	30.5
Conde, Ba	11.49	37.37	24	1250	0-200	S	III	*E. grandis*	7	61.9	54.5
Eclides da Cunha, Ba	10.31	39.01	24	500	500-1000	S/C	I	*E. camaldul.* *E. exerta*	5	25.6	29.6
Contendas do Sincora, Ba	13.45	41.02	22	700	200-500	C	I	*E. camaldul.*	4	8.0	5.9
Caetite, Ba	14.04	42.29	22	1100	1000-2000	S	II/IV	*E. camaldul.*	5	60.8	45.2
Banballia, Ce	7.19	39.17	21	650	500-900	S/C	I	*E. tereticornis*	5	26.0	18.3
Tiangua, Ce	3.44	40.59	26	1100	500-1000	S	II	*E. citroid* *E. tereticornis*	3	48.0	46.9
Pacajus, Ce	4.10	38.28	26	1000	0-200	S	III	*E. grandis*	5	98.3	89.3
Sousa, Pb	6.45	38.14	26	1000	200-500	R/S	IV	*E. camaldul*	8	39.7	32.4
Pedio Avelino, RN	5.31	36.23	26	500	0-200	R/S	IV	*E. camaldul*	8	5.9	4.7

(a) Most of these trials were carried out on 10 to 20 ha plots. Peak yield refers to the highest yield achieved on a small area within the plot. The average yield refers to the entire area. Source: Centro Nacional de Florestas, Empresa Brasileira de Pesquisa Agropecuaria.

(b) C = Clay, R = rocky, S = sandy.

(c) I = especially well-suited to support tree growth, II = average suitability, III = useable with restrictions, IV = cannot be used for trees.

(d) All are species within the genus *Eucalyptus*. Spacing of trees in all trials was 3 by 2 meters.

The expected yields by BCR are based on existing plantation technology and do not take into consideration likely improvements in yields in the future. The yields are considerably less than yields being routinely achieved in other regions of Brazil that are better suited to plant growth.

Considering the distribution of bioclimatic regions and the yields associated with each of these, the total plantation production potential in the Northeast is about 1340 million m^3/yr of wood, or some 12.6 EJ/yr (Table 10). This is large in comparison to the total primary energy use in the Northeast in 1990 of about 1.1 EJ. Three states account for 93% of the potential wood energy production: Maranhao (39%), Bahia (31%), and Piaui (23%). Half or more of the total area of Maranhao and Piaui and 30% of Bahia are estimated to be suitable for plantations (Table 10).

Table 10. State-by-state distribution of bioclimatic regions, average expected plantation yields, and total wood production in Northeast Brazil.[a]

		Bioclimatic Region							*Total potential wood production in millions of*	
	Total state area[b]	I	II	III	IV	V		*Weighted average yield*		
		Average yield (m^3/ha/year)								
		44	*33*	*28*	*15*	*6*				
State	(10^3 ha)	*Area (1000 hectares)*					*Total*	(m^3/ha/yr)	(m^3/yr)	(GJ/yr)[c]
Alagoas	2911	32	318	126	21	2	498	31.6	16	148
Bahia	56698	589	3636	7511	3761	732	16228	25.7	417	3920
Ceara	14569	62	80	303	499	--	944	22.6	21	201
Maranhao	32956	3233	3396	9533	41	--	16203	32.2	522	4905
Paraiba	5396	1	161	172	172	--	506	25.2	13	120
Pernambuco	10102	138	108	215	319	342	1120	20.0	22	211
Piaui	25466	--	--	7585	6527	--	14112	22.0	310	2917
R.G. de Norte	5317	--	40	111	221	89	461	17.9	8	78
Sergipe	2186	--	--	384	4	--	387	27.9	11	102
TOTALS	155600	4054	7738	25939	11563	1165	50459	26.6	1341	12600
Energy (10^6 GJ/yr)		1677	2400	6827	1630	66	12600			

(a) Totals may not add due to rounding.

(b) From (IBGE, 1990).

(c) Assuming 0.47 dry tonnes per m^3 and 20 GJ per dry tonne.

3.2.2. Plantation economics

The CHESF studies also included cost data from major commercial plantation-wood producers in the Northeast and in the state of Minas Gerais, which borders the Northeast. The basic cost components include land, nursery production of saplings, planting, cultivation, administration, research and development, harvesting, and transport. We present average values of the collected data, which are representive of the actual costs in Northeast Brazil.

In an actual plantation, typical practice in Brazil today is to leave 20-30% of the area in a natural or otherwise undisturbed state to enhance productivity and environmental harmony, as illustrated by the photograph (Fig. 5) of a commercial plantation. Thus, for each planted hectare, 1.43 ha (assuming a 30% margin) must actually be considered in the cost assessment.

The largest components of the total levelized cost of plantation wood production are planting (excluding land costs), harvesting, and transport (Table 11). Estimated average wood costs range from a low of \$1.09/GJ from plantations in BCR I, up to \$3.71/GJ in BCR V, with a weighted average for the Northeast of \$1.36/GJ.[10] Table 11 also shows a high and low cost estimate for each region, reflecting the wide variation in land and planting cost data provided by the wood producers.

The sensitivity of total wood cost to assumed plantation yield is clearly seen in Fig. 6. Wood costs rise particularly sharply for yields below about 8 dry tonnes per hectare per year (17 m^3/ha/yr). Average yields by state, which are also indicated on Fig. 6, all fall above this "knee" in the curve. While costs are relatively high for BCRs IV and V, relatively little of the wood production potential exists in these regions (Fig. 7). Over 86% of the wood production would be at an average cost less than \$1.35/GJ. It is worth re-emphasizing that these costs are based on current commercial plantation technology and do not consider any cost reductions that might occur through innovation and/or learning in the future.

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[10] For a 10% discount rate. See notes to Table 11 for additional details of the cost calculations.

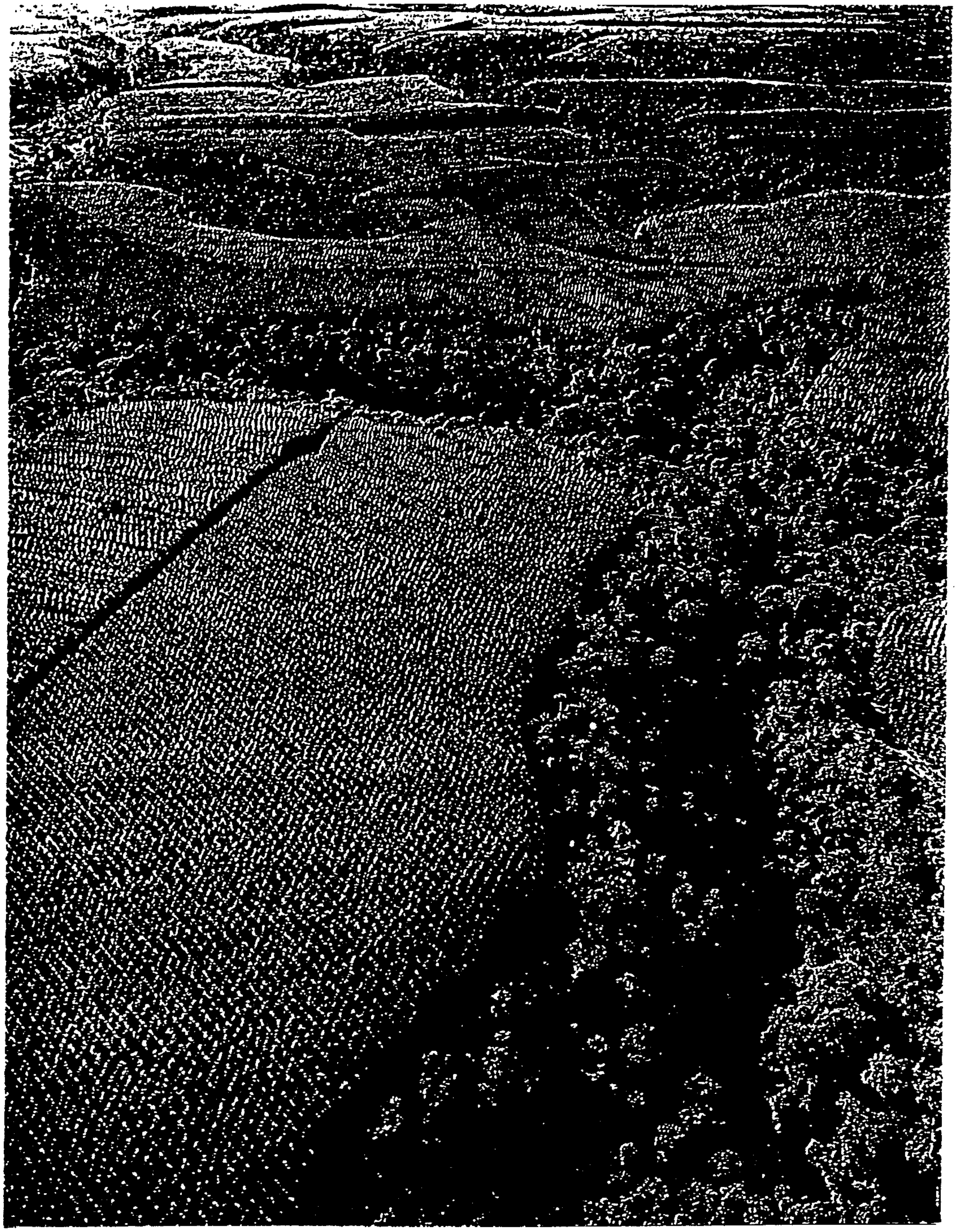

Figure 5. Aerial photograph of a commercial *Eucalyptus* plantation operated by Aracruz Celulose S.A. in the state of Espirito Santo, located near the Atlantic coast of Brazil 400 km north of Rio de Janeiro. Note that stands of *Eucalyptus* are interspersed with native trees. At Aracruz, native trees account for about 20% of the planted area. Native trees, especially fruit-bearing ones, attract birds, which helps control insect pests in the *Eucalyptus* stands. (Photograph from Aracruz Celulose S.A. publication, "Technology Social Progress, and the Environment.")

Table 11. Average levelized costs ($ per GJ) of wood from plantations by bioclimatic region.[a]

	Bioclimatic region					*Average*
Levelized cost[b] ($/GJ)	I	II	III	IV	V	*Northeast*
Plantation Establishment						
Nursery production	0.03	0.04	0.05	0.09	0.24	0.05
Land[c]	0.08	0.11	0.13	0.25	0.61	0.14
Planting	0.21	0.28	0.33	0.62	1.54	0.35
Administration	0.01	0.01	0.01	0.02	0.05	0.01
Subtotal	**0.33**	**0.44**	**0.52**	**0.98**	**2.44**	**0.55**
Plantation Maintenance						
Management	0.01	0.01	0.01	0.02	0.04	0.01
Cultivation	0.05	0.07	0.09	0.16	0.40	0.09
Research	0.02	0.03	0.03	0.06	0.15	0.03
Harvest	0.35	0.35	0.35	0.35	0.35	0.35
Transport	0.33	0.33	0.33	0.33	0.33	0.33
Subtotal	**0.76**	**0.79**	**0.81**	**0.92**	**1.27**	**0.81**
Total	**1.09**	**1.23**	**1.33**	**1.90**	**3.71**	**1.36**
Cost range[d]						
High	1.21	1.39	1.52	2.25	4.60	1.16
Low	0.97	1.07	1.14	1.54	2.82	1.56

(a) Costs for delivered wood logs with 33% moisture content, based on the average of cost data provided by some major commercial plantation operators in Brazil today and on the average annual yields by bioclimatic region indicated in Table 10

(b) The levelized production cost in $/GJ is given by

$$\{[\mathrm{CRF}(i,N)\cdot E + i\cdot L + M)]/Y_{\mathrm{L}}\} + H + T$$

where the variables (and average values used in the calculations) are as follows:

i = real discount rate (0.10)
N = plantation lifetime (18 years)
$\mathrm{CRF}(i,N)$ = capital recovery factory = $i/[1 - (1 + i)^{-N}]$
E = establishment costs (sum of $90.2/ha for nursery production of samplings, $589/ha for planting, and $18.8/ha for administration)
L = land price ($200/ha divided by 0.7 use factor). The average fraction of a given area that is planted with harvestable trees is assumed to be 70% of the total area.
M = annualized maintenance cost, including the following costs in each of years 1 through 18: management ($1.9/ha/yr), cultivation ($18.7/ha/yr), and research ($7/ha/yr).
Y_L = levelized yield = $\mathrm{CRF}(i,N)\cdot\sum_t Y_t\cdot(1+i)^{-t}$
t = year in which harvests are taken (6, 12, 18)
Y_t = yield (GJ) at each harvest. Of the total yield during the 18-year rotation, the first cut is assumed to produce 38.2% of the total. The second and third cuts produce 34.4% and 27.4%, respectively.
H = levelized harvest cost ($0.35/GJ)
T = levelized transport cost for 85 km haul ($0.33/GJ)

(c) Land cost is a rent, since land is assumed to hold its value in real terms.

(d) The high and low variants of the levelized cost are based on the use of the high and low estimates for land and for planting, which showed the largest variation among the cost components in the data from the commercial operations surveyed. Land costs ranged from $100-$300/ha and planting costs ranged from $367-$811 per planted hectare.

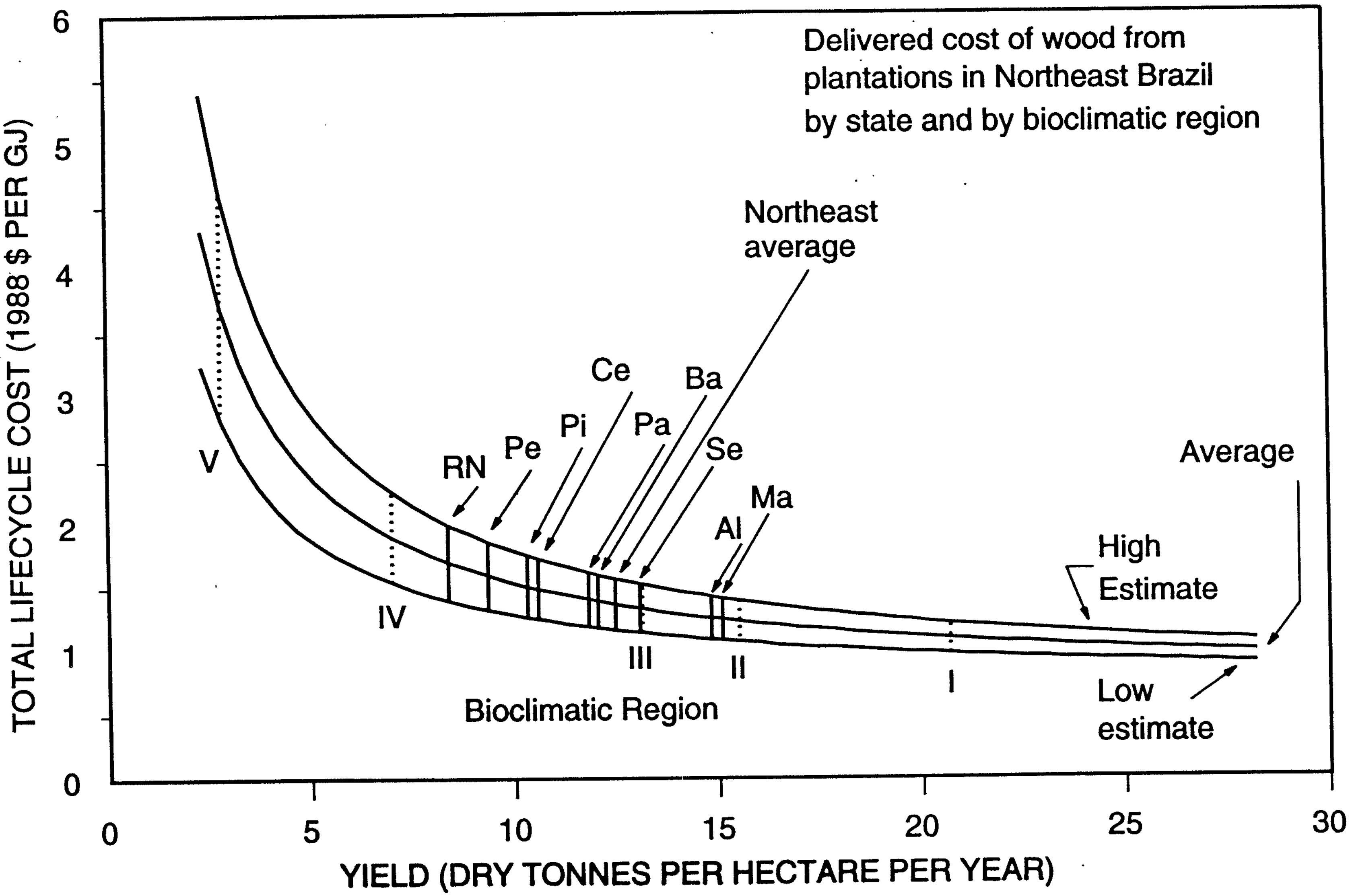

Figure 6. Estimated high, low, and average costs of plantation grown wood versus plantation yield. Average costs by bioclimatic region are shown, as are the average costs by individual state in the Northeast. (See Table 11.)

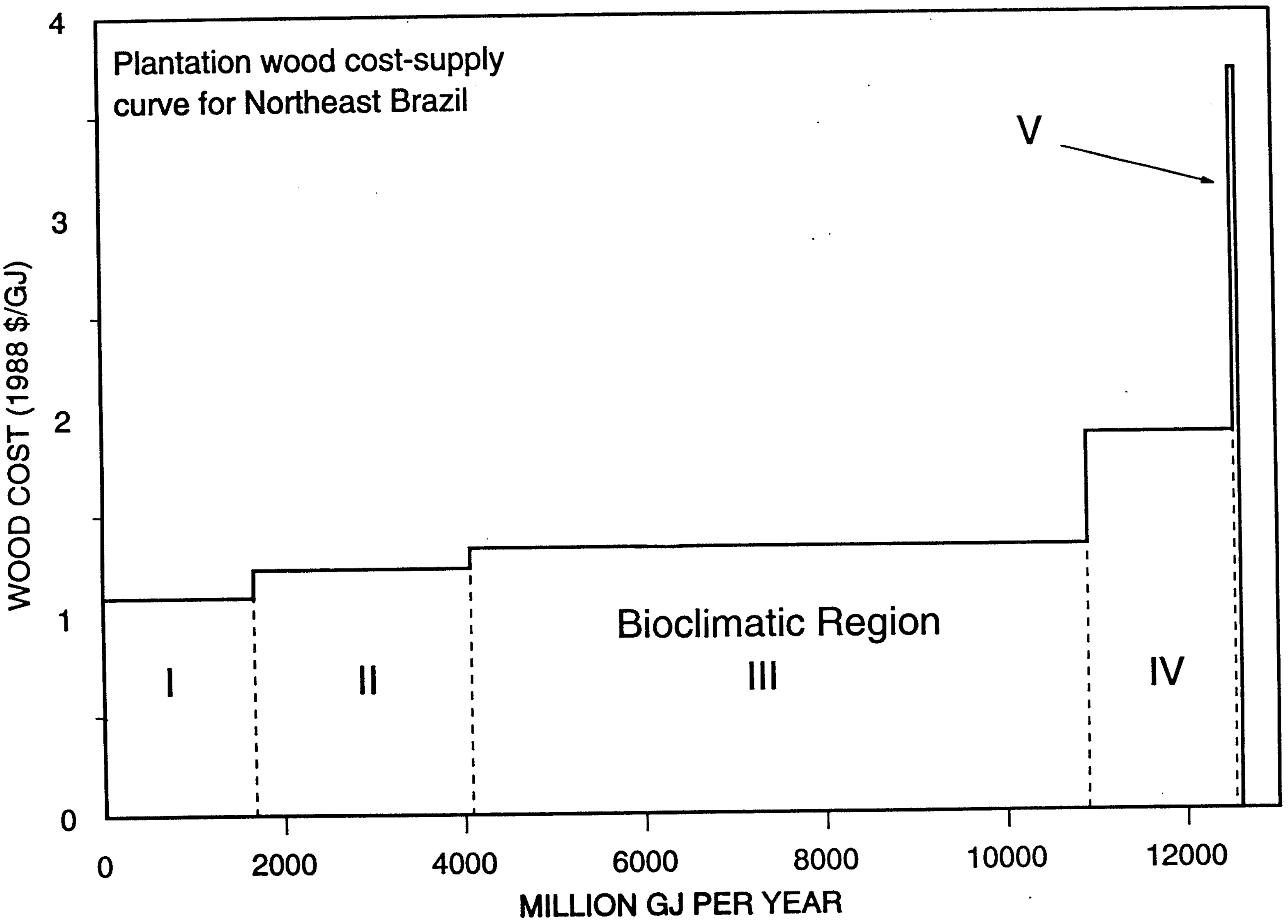

Figure 7. Plantation wood cost-supply curve for Northeast Brazil. The average cost and the estimated total volume of wood that can be produced in each of the five bioclimatic regions are shown.

3.2.3. Plantation employment

Employment generation is a potential social benefit of large-scale bioenergy plantation development. The likely employment generation for plantations in the Northeast region are quantified here based on employment data provided by companies maintaining commercial *Eucalyptus* plantations (Carpentieri, 1991).

Table 12 summarizes the number of person-hours per hectare for each plantation activity over an assumed 18-year rotation, giving a total average of 2.7 jobs per square km, with a range from 1.9 to 3.6 jobs/km^2. For the range of capital investment (including all establishment costs, Table 11) reported by commercial plantation operators ($719 to $1349 per planted hectare), the investment per job created averages about $33,000. This investment requirement is typical for agricultural jobs and is about one-quarter the level typically required to establish an industrial job in Northeast Brazil (Banco do Nordeste, 1990) and about 1/30th the level needed to establish a job at a hydroelectric power plant.

Table 12. Estimated labor requirements for commercial tree plantations in Northeast Brazil.[a]

	Person-hours / hectare[b,c]		
	Low	*High*	*Average*
Seedling production	27.2	74.2	50.8
Planting	79.0	296.8	150.1
Cultivation	88.2	207.0	141.5
Administration	28.8	28.8	28.8
Research	88.7	88.7	88.7
Harvest	157.3	393.3	327.2
Transport	210.0	210.0	210.0
TOTAL (p-h/ha)	679.2	1298.8	997.1
(jobs/km^2)[d]	1.9	3.6	2.7

(a) Source: (Carpentieri, 1991).

(b) Total person-hours required over an assumed 18-year rotation.

(c) The low and high estimates are based on the lowest and highest labor requirements for each activity reported by any of the companies interviewed [see note (a)]. The average is that of all reported figures.

(d) Assuming one job consists of 36,432 person hours over the rotation period (8 hours/day * 23 days/mon * 11 mon/yr * 18 years/rotation).

4. Technologies for Electricity Production from Biomass

The current state-of-the-art technology for producing electricity from biomass is the condensing steam turbine, in which the biomass is burned in a boiler to produce steam, which is expanded through a turbine driving a generator (Fig. 8). The technology has been in use for over 100 years. It is particularly attractive because it is robust in operation and can accept a wide variety of biomass feedstocks. A major drawback is the relatively high unit capital cost of the technology at the modest scales (50-60 MW or less) that characterize biomass applications. It also has relatively low operating efficiency, and thus has historically depended for economic success on the use of low cost biomass fuel, such as that available at a sugarmill, where bagasse has been considered essentially "free." Furthermore, there is little prospect for improving efficiency or lowering unit capital costs of the technology significantly in the future (Williams and Larson, 1992).

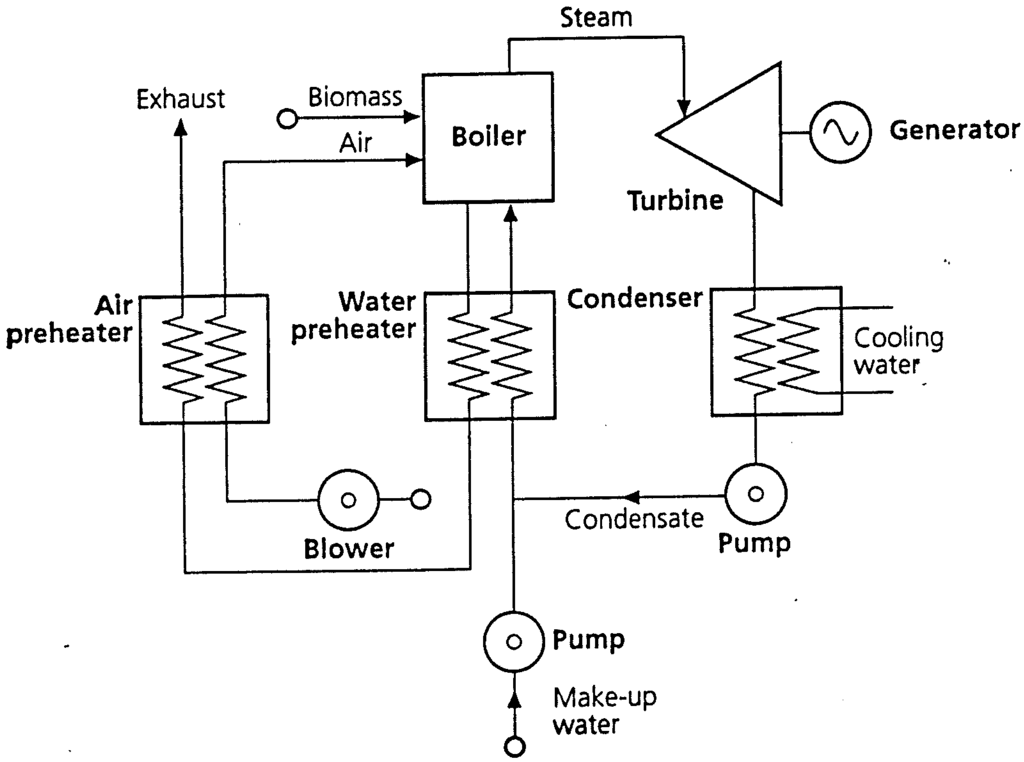

Figure 8. Conventional technology for producing electricity from biomass: a condensing steam-turbine (CST) cycle. Biomass is burned in a boiler to raise pressurized steam that is then expanded through a steam turbine driving a generator.

A promising alternative to the steam turbine is the gas turbine fueled by gas produced through the thermochemical gasification of biomass (Williams and Larson, 1992). The simplest gas turbine cycle is the open cycle (Fig. 9a), in which the hot exhaust of the turbine is discharged directly to the atmosphere. In more efficient variants, the hot exhaust is used to raise steam in a heat recovery steam generator. The steam can be used in any of several ways (Fig. 9): for meeting process heating needs in a cogeneration system; for injecting back into the gas turbine to raise power output and generating efficiency in a steam-injected gas turbine (STIG) cycle; or for expanding through a steam turbine to boost power output and efficiency in a gas turbine/steam turbine combined cycle (GTCC). A variety of other advanced cycle configurations have been identified that could be developed in the future to yield higher efficiencies (Williams and Larson, 1989; Williams and Larson, 1992).

Gas turbines, unlike steam turbines, are characterized by lower unit capital costs at modest scale, and the most efficient cycles are considerably more efficient than comparably-sized steam turbines. Furthermore, gas turbine cycles for stationary power generation, unlike steam turbines, have seen dramatic improvements in efficiency and capital cost over the past fifteen years. This progress was initially driven by the growing demand for high efficiency cogeneration systems from the private sector in the US after passage of the 1978 Public Utility Regulatory Policies Act.[11] ("PURPA" was the path-breaking legislation requiring electric utilities to purchase electricity from cogenerators at a price equal to the cost the utility would incur to otherwise provide that electricity.) The higher efficiency of gas turbine cogeneration systems often permits cogenerators to produce electricity in excess of onsite needs for sale to the utility (Larson & Williams, 1986). Subsequent to the cogeneration "boom" in the US, gas turbines have become recognized worldwide by utilities as the technology of choice for central station power generation because of their low capital cost, short construction lead times, and high efficiencies.

While natural gas is the preferred gas turbine fuel today, the recognition of near-term limits on the availability of natural gas resources contrasted with the abundance of coal, has

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[11] Development of gas turbines for stationary power generation have benefitted in the past, and will continue to benefit from R&D work for military aircraft applications and efforts to improve efficiency in response to demands of commercial airlines for higher efficiency (Williams and Larson, 1989).

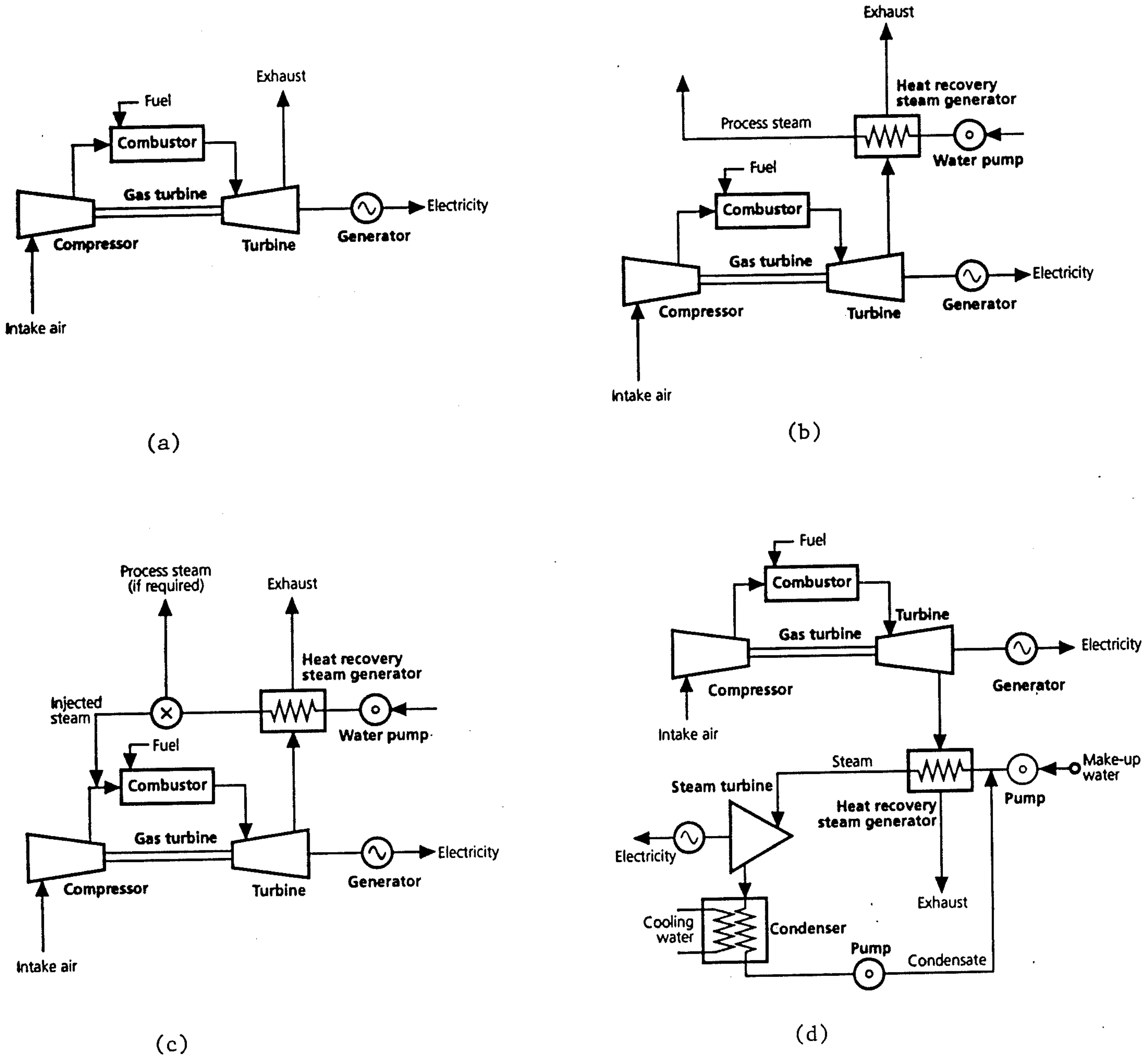

Figure 9. Alternative commercial gas turbine cycles fueled with natural gas. In each cycle, the pressurized fuel is burned with compressed air, and the combustion products expand through a turbine driving a generator. The efficiency of each cycle is determined to a large extent by the extent to which the hot exhaust of the turbine is recovered. In the open cycle (≈ 32% efficiency), (a), the heat is not recovered. In the cogeneration cycle, (b), the heat is used to raise steam in a heat recovery steam generator for use in an industrial process; overall efficiency of fuel use is thus higher, but the efficiency of electricity production is the same as for an open cycle. In the steam-injected cycle (≈ 38%), (c), steam is also raised, but is injected into the combustor to boost efficiency and electricity output. In the gas turbine/steam turbine combined cycle (≈ 41%), (d), steam is raised and used to produce additonal power in a steam turbine.

stimulated hundreds of millions of dollars of R&D efforts to adapt coal as a fuel for the gas turbine by first thermochemically gasifying it. Much of the development work on coal-gasifier/gas turbine systems is directly relevant to biomass-gasifier/gas turbines (BIG/GTs) (Larson, et al., 1989; Williams and Larson, 1992). Figure 10 shows one possible configuration of a biomass-gasifier gas-turbine/combined cycle. There are now several efforts underway worldwide to demonstrate the BIG/GT technology, including one in Brazil (see Section 6). It now appears that the BIG/GT technology will be available for commercial power generating applications before the turn of the century.

Comparative performance and cost estimates for biomass-fired steam turbine and gas turbine systems show the clear capital cost and efficiency advantages of the gas turbine in either cogeneration applications in the sugarcane processing industries (Table 13) or stand-alone electricity generation (Table 14).

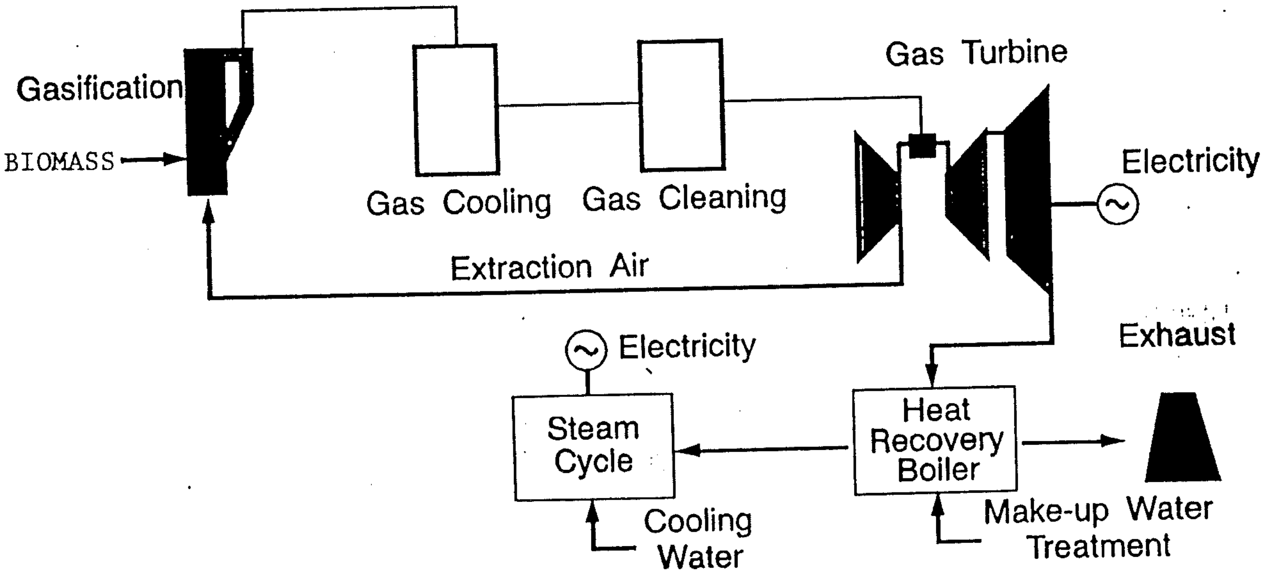

Figure 10. One possible configuration of a biomass-gasifier/gas-turbine combined cycle (BIG/GTCC). The biomass is converted into a combustible gas in a pressurized gasifier. After cooling and cleaning, the gas is burned in a gas turbine/steam turbine combined cycle (see Fig. 9d).

Table 13. Characteristics of steam turbine and gas turbine cogeneration technology options considered here for use in sugarcane processing industry (Carpentieri, 1991).

	Condensing extraction steam turbine	*Gasifier steam-injected gas turbine*
Installed power plant capacity per unit of cane processing capacity (kW per tc/d)[a]	4.20	9.39
Electricity efficiency (% HHV)[b]		
With steam production	13.0	28.6
With out steam prod.	20.3	32.5
Surplus electricity prod. (kWh/tc)		
On-season (bagasse)	87.4	210.2
Off-season (tops & leaves)[c]	95.9 (122.6)	153.6 (196.2)
COSTS		
Installed capital cost ($/kW)	2100	1170
Operation and maintenance (c/kWh)	0.75	0.60
Fuel ($/GJ)		
Bagasse[d]	1.18	1.68
Tops/leaves[e]	1.91	1.49

(a) Based on capacity that could be supported by a factory crushing 1714 tc/day, the standard sized alcohol distillery unit in Brazil today: 7.2 MW for CEST or 16.1 MW for STIG.

(b) From (Larson, Williams, Ogden, and Hylton, 1990), assuming 50% moisture content fuel for CEST and 15% moisture content fuel for STIG.

(c) The number out of (in) parentheses is based on estimates of recoverable tops and leaves under near future (advanced future) conditions. See Table 4.

(d) Bagasse is often considered to be available at no cost at the mill. Here, we assume the bagasse cost for the CEST corresponds to a bagasse cost of $20/dry tonne, which is considered an opportunity cost. In the STIG case, an additional $0.50/GJ is included for drying.

(e) The cost for recovery of tops and leaves are estimated in (Carpentieri, 1991), based on (Howe and Sreesangkom, 1990).

Table 14. Performance, cost, and employment estimates for stand-alone biomass power plants.[a]

	Condensing steam turbine[b]	*Gasifier open-cycle gas turbine*	*Gasifier steam-injected gas turbine*	*Gasifier gas turbine / steam turbine combined cycle*
Unit Capacity (MW)	50	60	60	60
Efficiency (%HHV)[c]	21	25	35	40
Investment cost ($/kW)	2351	947	1170	1113
Fixed O&M cost ($/kW-yr)	29.2	26.7	26.7	26.7
Variable O&M ($/kWh)	0.003	0.001	0.001	0.001
Employment				
Construction jobs/MW	3.46	3.46	3.46	3.46
Fixed operating jobs/MW	0.893	0.683	0.517	0.517
Variable operating jobs/GWh	0.130	0.099	0.061	0.055

(a) Based on (Carpentieri, 1991), unless indicated otherwise.

(b) Steam conditions: 6 MPa, 480 C.

(c) Authors' own estimates, assuming wood with 33% moisture content for the CST and 15% moisture content for the GT options.

5. Biomass-Electricity Development for Northeast Brazil

What impact might biomass-based power generation have in Northeast Brazil in the medium to long term? We begin to answer this question by combining our analyses of the potential for producing sugarcane residues and plantation fuelwood in the Northeast with our estimates of the performance of advanced technologies for producing electricity from biomass to estimate the total potential contribution that biomass might make to electricity supply in the Northeast region.

5.1. Technical Potential and Cost

Table 15 shows a state-by-state estimate of the potential supply of electricity from sugarcane residues for the three residue production scenarios considered above and for steam turbine (CEST) and gas turbine (STIG) cogeneration technologies. Compared to the total utility electricity supply in the Northeast in 1990 of about 31 TWh, the potential electricity production at sugarcane processing facilities is significant, ranging from 6.1 TWh under the

Table 15. Electricity production potential (in excess of the requirements for sugarcane processing) and cost from sugarcane residues in Northeast Brazil for the present, near future, and advanced future scenarios and for two alternative cogeneration technologies, assuming area planted with cane remains at 1989 level.[a]

	EXCESS ELECTRICITY PRODUCTION (Million kWh/year)					
	Present		*Near Future*		*Advanced Future*	
State	CEST	STIG	CEST	STIG	CEST	STIG
Alagoas	1993.5	4796.5	4803.9	9276.0	7083.8	13403.4
Bahia	319.4	768.4	769.6	1486.0	1134.8	2147.2
Ceara	249.2	599.6	600.5	1159.5	885.5	1675.4
Maranhao	173.0	416.1	416.8	804.8	614.6	1162.9
Paraiba	755.6	1817.9	1820.7	3515.7	2684.8	5080.0
Pernambuco	2105.7	5066.3	5074.1	9797.8	7083.8	13403.4
Piaui	67.2	161.7	161.9	312.7	238.8	451.8
R.G. de Norte	250.8	603.5	604.5	1167.2	891.4	1686.6
Sergipe	181.1	435.8	436.5	842.8	643.7	1217.9
TOTALS	6095.5	14665.7	14688.4	28362.5	21659.7	40982.6
Average cost of excess electricity production (c/kWh)[b]	13.45	6.70	8.11	4.83	7.06	4.40

(a) See Table 4 for characterizations of the three scenarios. See Table 5 for planted area and assumed productivities. Excess power generated per tonne of cane processed are as in Table 14. Note that in the "Present" scenario, electricity is produced only from bagasse (during an assumed 160 day milling season). CEST = condensing extraction steam turbine. STIG = steam-injected gas turbine.

(b) Calculated from costs and performance shown in Table 14.

"Present" scenario with CEST technology, up to 41 TWh/yr under the "Advanced Future" scenario with STIG technology. In the two future scenarios, the average cost of producing the electricity ranges from 7.1-8.1 c/kWh for CEST technology and 4.4-4.8 c/kWh for the STIG. The latter would be competitive with marginal costs of anticipated new hydroelectric supply in the Northeast (Fig. 2b).

The potential electricity supply from stand-alone power plants fed by wood from plantations is much greater than the sugarcane-based potential, ranging from 735 TWh/yr with condensing steam turbine technology (CST) up to 1,400 TWh/yr with gas turbine/steam turbine combined cycle technology (GTCC) (Table 16). Costs of electricity are in the same range as for the sugarcane facilities: 7.3 c/kWh for CST technology down to 4.3 c/kWh for GTCC systems.

Table 16. Potential electricity production and average cost in Northeast Brazil for four alternative central station biomass power generating technologies.

	Average delivered biomass cost ($/GJ)[c]	*Potential electricity production*[a] (10^9 kWh/yr)				*Electricity production cost*[b] (cents/kWh)			
		CST	GTOC	GSTIG	GTCC	CST	GTOC	GSTIG	GTCC
By State									
Alagoas	1.25	8.6	10.3	14.4	16.4	7.15	5.13	4.54	4.16
Bahia	1.39	228.7	272.2	381.1	435.6	7.39	5.33	4.68	4.29
Ceara	1.48	11.7	14.0	19.5	22.3	7.55	5.46	4.77	4.37
Maranhao	1.24	286.1	340.6	476.9	545.0	7.14	5.12	4.53	4.15
Paraiba	1.40	7.0	8.3	11.7	13.3	7.41	5.35	4.69	4.30
Pernambuco	1.59	12.3	14.7	20.5	23.4	7.74	5.62	4.89	4.47
Piaui	1.50	170.2	202.6	283.6	324.1	7.58	5.49	4.79	4.39
R.G. de Norte	1.69	4.6	5.4	7.6	8.7	7.91	5.76	4.99	4.56
Sergipe	1.33	6.0	7.1	9.9	11.3	7.29	5.25	4.62	4.23
By Bioclimatic Region									
I	1.09	97.8	116.5	163.0	186.3	6.88	4.90	4.37	4.02
II	1.23	140.0	166.7	233.3	266.7	7.12	5.10	4.51	4.14
III	1.33	398.2	474.1	663.7	758.6	7.29	5.25	4.62	4.23
IV	1.90	95.1	113.2	158.5	181.1	8.27	6.07	5.20	4.75
V	3.71	3.9	4.6	6.4	7.3	11.37	8.67	7.07	6.38
Total NE	1.36	735.1	875.1	1225.2	1400.2	7.35	5.29	4.65	4.26

(a) Assuming full plantation biomass production potential (Table 10) is used for electricity production. CST, GTOC, GSTIG, and GTCC refer to Condensing Steam Turbine, Gas Turbine Open Cycle, Steam-Injected Gas Turbine, and Gas Turbine/Steam Turbine Combined Cycle, respectively.

(b) Assuming the capital and operation and maintenance costs from Table 13. In addition to the delivered biomass cost shown above, the fuel cost for the steam turbine option includes an additional $0.50/GJ, the assumed cost of chipping. An additional cost of $1/GJ is included for the gas turbine options to account for the cost of drying as well as chipping.

(c) Assuming the average state-by-state yields in Table 10, together with the costing assumptions in Table 11, note (b). The delivered wood is assumed to have a moisture content of 33%. The delivered cost shown here does not include the cost of chipping or drying--see note (b).

5.2. Hydro-and Biomass-Intensive Electricity Development Scenarios

It is unlikely that all of the biomass-electricity potential we estimate here would actually be realized in practice. On the other hand, the potential is large enough that it is likely that realizing a small fraction of the potential could have a noticeable impact on the Northeast's utility system. To explore the extent to which the biomass-electric potential might be realized in practice, we have constructed two alternative scenarios for the development of the Northeast's utility system to the year 2015. In both scenarios, we assume that electricity demand grows at 5% per year from 1990. This is in the mid range of projections that have been made by CHESF (CHESF, 1991b). Our first scenario, called HYDRO, is based on CHESF plans for continued expansion of the hydroelectric system. The second, BIOMASS, is intended to be a plausible scenario of how biomass could be introduced into the Northeast utility system.

In the HYDRO scenario, CHESF's current proposals for expanding the hydroelectric supply system (Table 17) are assumed to be implemented. The proposals call for adding approximately 3,900 MW through the year 2000, most of which would come on line beginning in 1994 at a single site, Xingo I. The Northeast's total hydroelectric resource would be fully exploited after installation of an additional 2,255 MW of capacity. While CHESF has not set target dates for commissioning all of this capacity, with a demand growth rate of 5% per year, all of the capacity would have to be operating by about 2005. From 2005 to 2015 an additional 11,000 MW of hydro capacity would need to be tapped in the North (Amazon) region to supply power to the Northeast. Assuming that the Northeast would receive 60% of power from hydro sites in the North, the needed 11,000 MW of capacity would exhaust the 18,250 MW of capacity that has already been identified in the North (Table 17) and which represents 19% of the total hydro potential of the North (Table 2).

In the BIOMASS scenario, we assume that no new hydropower plants come on line after the Itapebi plant in the year 2000 (see Table 17). Biomass is assumed to begin making a contribution in 2000 in the form of electricity from CEST systems at sugarcane processing facilities operating under conditions in the "near future" scenario discussed earlier. We assume that 300 MW of CEST capacity are operating by the year 2000 and that the installed capacity grows 20% per year until 2004. In 2005, 300 MW of GSTIG technology, operating

Table 17. Historical and planned hydropower plants in CHESF (Northeast) territory & North regions of Brazil.[a]

Plant name	*Planned commission date*[b]	*Plant capacity* (MW)	*Electricity production capability* (MWyr/yr)	*Investment cost w / idc in 1988$*[c] ($/kW)	*Electricity production cost*[d] (c/kWh)	*Maximum flooded area* (km²)
CHESF REGION						
Currently installed						
P.A. I/II/III	1954/61/71	180/480/864	106/282/507	119	0.31	5
Boa Esparanca I	1970	108	94	1144	1.59	362
Moxoto	1977	440	234	980	2.20	93
Sobradinho	1979	1045	1067	1135	1.36	4268
Paulo Afonso IV	1979	2460	287	254	2.58	15
Itaparica I	1987	1500	890	1635	3.25	832
Boa Esperanca II	1990	126	32	662	3.08	356
SUBTOTAL		7203	3499			5931
Future additions						
Xingo I	1994	3000	2094	1066	1.84	85
Sacos	1999 (Mar)	114	66	1181	2.43	14
Pedra do Cavalo	1999 (Dec)	300	95	1207	4.47	164
Araca	2000	120	74	1094	2.12	119
Itapebi	2000	375	208	1774	3.76	65
Gatos III		36	28	1633	2.50	100
Gatos I		30	17	1375	2.87	113
Paratinga		440	184	1453	4.08	2300
Pedra Branca		768	400	2391	5.36	816
Belem		477	241	2340	5.41	248
Salto da Divisa		174	95	3188	6.80	731
Pao de Acucar		330	127	2588	7.82	32
SUBTOTAL		6164	3910			4787
TOTAL CHESF REGION		13367	7409			10718
NORTH REGION (*future additions*)						
Belo Monte		11000	3800	901	4.31	1225
Serra Quebrada		1450	875	1640	4.43	370
Estreito		1200	744	1934	4.89	710
Tupirantins		1000	590	2227	5.65	545
Santa Isabel		2200	1235	2141	5.69	2900[e]
Lageado		800	413	2014	5.79	630
Ipueiras		600	332	2594	6.70	1310
TOTAL NORTH REGION		18250	7989			7690

(a) Source: personal communication from Divisao de Planejamento de Geracao do Departamento de Planejamento de Geracao e Mercado, CHESF, Recife.

(b) Where no commissioning date has yet been estimated, the plants are ordered by increasing total production cost.

(c) Excluding transmission and distribution costs. (idc = interest during construction) Costs for plants in the CHESF region were obtained by converting Cruzeiro values of December 1991 into dollars (at 959.64 Cr/$) and then using the US GNP deflator to express the costs in 1988 dollars. For the plants in the North Region, original costs were in March 1990 Cruzerios and were converted at 37.82 Cr/$.

(d) For a 10% discount rate; 50-year plant life; O&M and transmission costs of $0.78/MWh and $0.0/MWh for plants in the CHESF region and $1.02/MWh and $12/MWh for plants in the North region.

(e) Preliminary estimate.

within a cane processing industry characterized by the "advanced future" scenario, is assumed to be brought on line and to grow at 20% per year. Stand-alone biomass gasifier/GTCC power plants using plantation fuelwood are assumed to first come on line in 2003, when they would be required to make up for a shortfall in power from hydro and cane sources. (Plantation establishment activity is assumed to begin in 1997 in order for the first cutting to provide fuel in 2003.) The wood-GTCC capacity installed in 2003 is 157 MW. To keep up with growing demand, the wood capacity grows about 30% per year to 2015. Fig. 11 shows the evolution of electricity supply in the BIOMASS scenario.

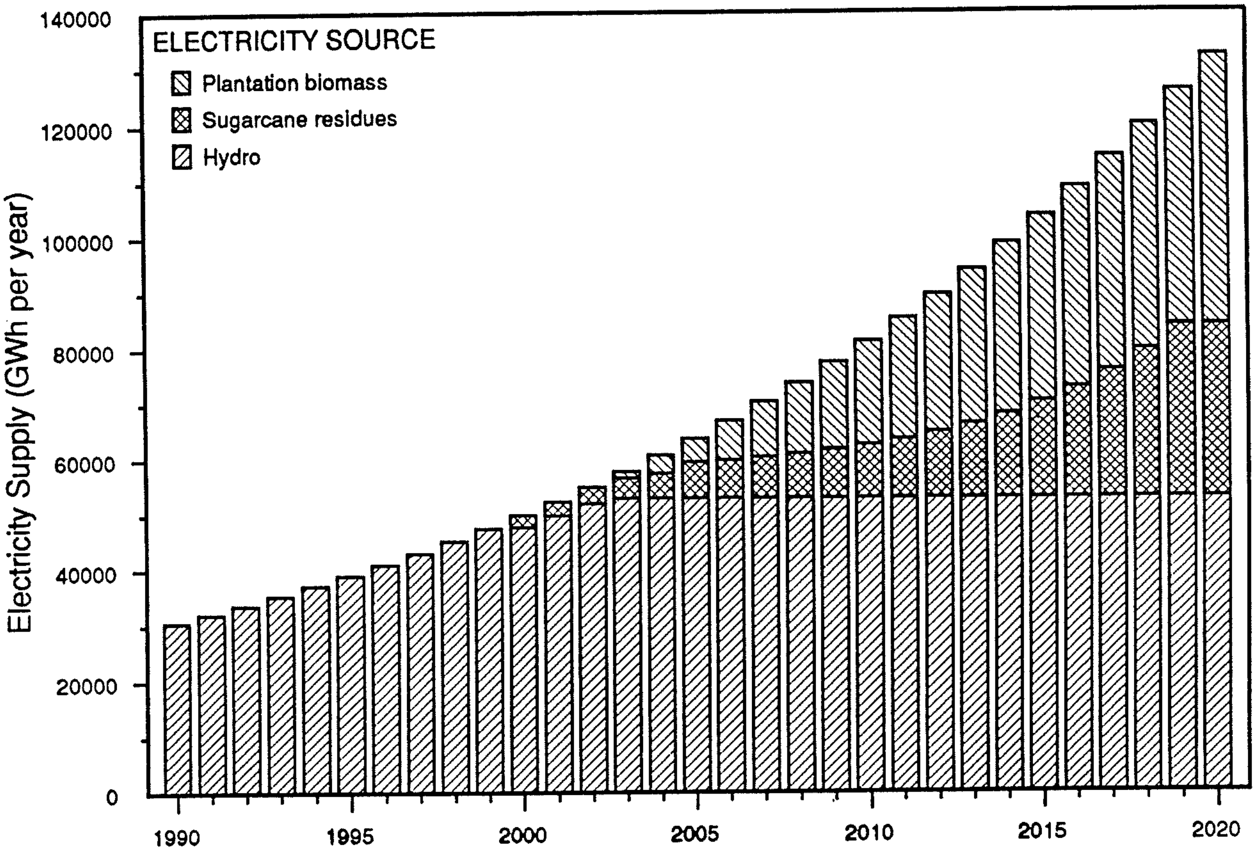

Figure 11. Evolution of the electricity supply mix in Northeast Brazil to the year 2020 under the BIOMASS scenario described in the text. Total electricity generation is assumed to grow 5% per year from 1990.

The BIOMASS scenario considers only wood supply from plantations in bioclimatic regions I, II and III, as these would be the most attractive economically. Furthermore, we consider that only half of region III would be suitable for GTCC power generation due to a shortage of water for power plant cooling in the other half of this region.[12] The plantation fuelwood converted to electricity in 2015 accounts for about 4% of the total potential from bioclimatic regions I, II and half of III, or about 2.4% of the total wood potential of the Northeast.

Table 18 compares salient features of the HYDRO and BIOMASS scenarios. The HYDRO scenario involves an addition of 17 GW of new capacity between 1990 and 2015, compared to 11 GW in the BIOMASS scenario. Average unit investment costs (including transmission costs of $300/kW for plants in the North region) are 18% higher in the HYDRO scenario than the BIOMASS scenario, but the total required capital investment from 1990 to 2015 in the HYDRO case is nearly twice as large as in the BIOMASS case ($26.7 versus $14.3 billion). The higher capacity and capital investment requirements for the HYDRO scenario reflect the diminishing number of low-cost hydro sites, the lower average capacity utilization rate for hydro plants (45-55%) compared to biomass-fired plants (80-85%), and the added transmission costs for hydro plants in the North region.

A significant difference between the HYDRO and BIOMASS scenarios is in the rates of capacity addition relative to the rate of demand growth (Fig. 12). The HYDRO scenario involves periodic over-capacity situations, as large increments of power are added to the grid. Capacity additions in the BIOMASS scenario track demand growth directly, which would facilitate planning and financing. The larger number of power generating units in the BIOMASS scenario (140 versus 27, Table 18) also adds to overall system reliability, since the shutdown of any one or two units at a time will have relatively little impact on the grid overall.[13]

Average electricity production costs in the BIOMASS scenario are slightly lower than in the HYDRO scenario. Marginal production costs are substantially lower (Table 18).

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[12] The GTOC cycle (Fig. 9), or other advanced cycles which consume no water, could be used in water-short regions, but we do not consider this possibility here.

[13] In practice, biomass units would probably be built in clusters of four or five units located in relative proximity to each other, in part to facilitate maintenance.

Table 18. Summary comparison of alternative electric system scenarios in Northeast Brazil for an assumed electricity demand growth rate of 5% per year, 1990-2015.

	HYDRO SCENARIO	**BIOMASS SCENARIO**			
		Hydro	Cane	Wood	Total
Generating capacity					
Added MW, 1990-2015	16,754	3,909	2,480	4,494	10,883
Total MW in 2015	23,957	11,112[a]	2,480	4,494	18,086
Number of generating units	27	14	50[b]	75[b]	140
Electricity generation (GWh)					
Total in 2015	103,555	52,875	17,214	33,465	103,555
Added, 1990-2015	72,975	22,295	17,214	33,465	72,975
Total (% of estimated potential)[c]	21%	10%	42%	2.4%	5.2%
Capital requirements (1988 US$)					
Total ($10^6\$$), 1990-2015	26,666[d]	4,491	3,609	6,568[e]	14,669
Average investment ($/kW)	1,592	1,149	1,455	1,462	1,348
Costs of electricity production in 2015					
Average system cost (c/kWh)	3.7	1.9	5.3	4.3	3.2
Marginal cost of new supply (c/kWh)	6.7	5.5[f]	4.4	4.3	4.3
Employment					
New jobs created, 1990 to 2015	25,131	5,864	96,764[g]	55,463[h]	158,091
Investment (1988 US$) per job	1,061,000	766,000	37,300	118,400	92,800
New land area required in NE region					
Total (km^2)	4,787[i]	447	--[j]	22,740[k]	23,187
Percent of total NE area	0.31%	0.03%	0.00%	1.46%	1.5%

(a) The only hydroelectric sites assumed to be added to the present hydro capacity in the biomass scenario are Xingo I, Sacos, Pedra do Cavalo, Araca, and Itapebi (Table 17).

(b) The number of cane processing sites in the Northeast today is about 120, only a fraction of which would be exporting electricity by 2015 under the scenario we have considered. The number of wood-fired generating sites is estimated assuming an average capacity of an individual plant to be 60 MW. (In practice individual units might be clustered into modules of 4 or 5 units each.)

(c) The total ultimate hydro GWh potential is estimated based on a total MW capacity potential of 113,300 MW (Table 2), which includes the potential in both the Northeast and North regions. The total ultimate wood and cane potentials are taken to be 1400 TWh (Table 16) and 41 TWh (Table 15), respectively.

(d) For plants located in the North, an average capital investment of $300 per kW above the costs shown in Table 17 is included for transmission to the Northeast.

(e) The total investment includes plantation establishment costs totalling $611 million incurred during the years 2010 to 2015. Because of the 6-year period before the first harvest, the plantation investments during these years do not lead to any electricity production until the period 2016 to 2021. The assumed plantation establishment cost is $213/kW. This assumes an average yield of 33 m^3/yr per planted hectare, conversion to electricity at 40% efficiency, an unplanted (natural-vegetation) area equal to 43% of the planted area, and a capital investment of $689/hectare.

(f) This is estimated to be the average cost of power from building and operating the 7 hydropower plants in the Northeast region that are not included in the Biomass scenario. See Table 17.

(g) This is the number of presently seasonal jobs that would be converted to full-time jobs.

(h) This total includes 13,099 jobs associated with establishing and maintaining plantations during the period 2010 to 2015. These plantations would not be harvested until after 2010. See note (e) above.

(i) This is the land area flooded by new hydro facilities in the Northeast region only. The area that would be flooded in the North region is an additional 7,700 km^2 (Table 17).

(j) Zero additional area is required for electricity from sugarcane, since the total planted area is assumed to remain at today's level.

(k) Only 70% of this area would be active plantation. The balance would be left in "natural" form. The total includes 8,870 km^2 of plantation area that would be established between 2010 and 2015, but which would not be harvested until the period 2016 to 2021. See note (e) above.

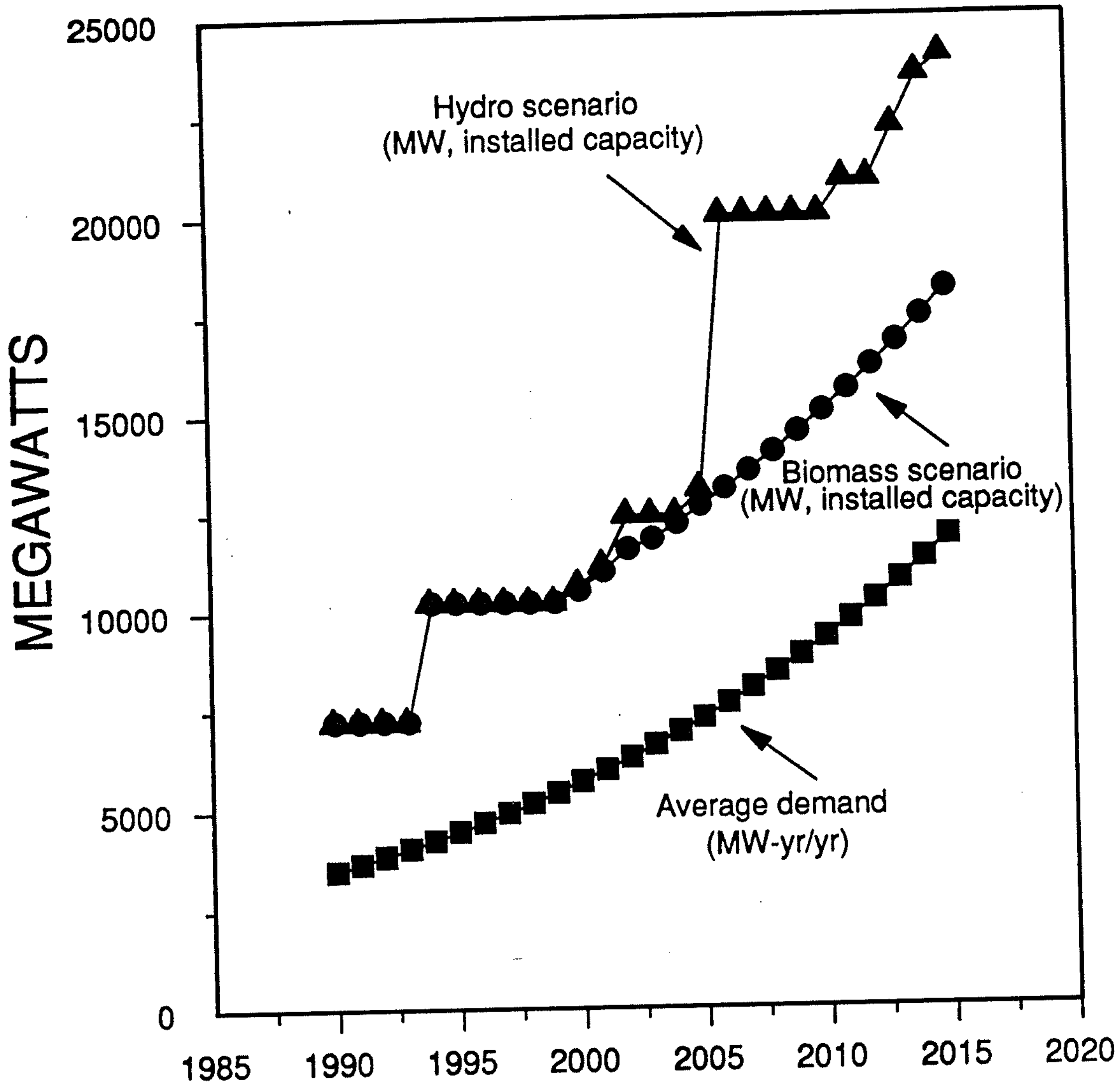

Figure 12. Average electricity demand (MW-yr/yr) in the HYDRO and BIOMASS scenarios, and a comparison of the installed capacity (MW) over time in each scenario.

The BIOMASS scenario would involve the creation of some 158,000 full-time jobs, compared to some 25,000 jobs in the HYDRO scenario (Table 18). In addition, 65% of the jobs in the HYDRO scenario would be in the North rather than Northeast region, while 100% of the jobs in the BIOMASS scenario would be in the Northeast. Sixty percent of the jobs in the BIOMASS scenario would be created in the sugarcane industry, where presently-seasonal jobs would be converted into full-time jobs through use of tops and leaves as a fuel in the off-season. The average investment per job created in the BIOMASS scenario ($93,000) would be an order of magnitude lower than in the HYDRO scenario.

There would be 130 new power generating units operating in 2015 in the Northeast in the BIOMASS scenario, compared to 12 new Northeast sites in the HYDRO scenario. Thus, the income derived from power generation, and the concentrations of other economic activity that might develop around power generating sites, would be more widely distributed in the BIOMASS scenario and would be located entirely in the Northeast region.

Finally, land use conflict would not appear to be a major concern in a biomass-intensive future in the time frame to 2015. New land in the Northeast that would need to be committed to electricity generation in the BIOMASS scenario would be about five times higher than in the HYDRO scenario, but would represent only 1.5% of the total land area of the Northeast (Table 18). It is also worth noting that the rate of plantation establishment required in the BIOMASS scenario (2.3 million hectares between 1997 and 2015) is one-half to one-third the rate at which commercial plantations have actually been established in Brazil during the past two decades.

5.3. Biomass Scenarios Under Alternative Electricity Demand Growth Rates

Some projections of electricity demand growth are higher than the 5% assumed above (CHESF, 1991b). While few projections are much lower than 5%, the average demand growth rate in the Northeast between 1985 and 1991 was about 3.5%. Thus, it is of interest to compare BIOMASS scenario results for a range of electricity demand growth rates. Table 19 shows such a comparison for growth rates of 4, 5 and 6 percent per year from 1990 to 2020, with the same basic assumptions used to develop the BIOMASS scenario in Table 18. We were unable to make comparisons with hydro-intensive scenarios as we did in Table 18, however, because hydro development plans beyond the plants shown in Table 17 were not available. Clearly, over the period to 2020, particularly with the higher growth rate, much more new hydro capacity would be required in a hydro-based scenario. It would be fair to say that the general conclusions drawn from the comparison in Table 18 between the HYDRO and BIOMASS scenarios will hold for analyses using different demand growth rates and carried out further into the future, as in Table 19.

Table 19. Comparison of biomass-based electricity scenarios for Northeast Brazil under different electricity demand growth rate assumptions. In each scenario, no new hydroelectric plants are built after 2000.

	Electricity Demand Growth Rate (% per year)		
	Four	***Five***	***Six***
Electricity generation			
Total GWh in 1990	30,580	30,580	30,580
Total GWh in 2020	99,183	132,165	175,636
From sugarcane	31,033	31,033	31,033
From plantations	15,275	48,257	91,728
From hydro	52,875	52,875	52,875
Fraction of ultimate potential used	5.0%	6.7%	8.9%
Installed generating capacity			
Total MW in 1990	7,203	7,203	7,203
Total MW in 2020	17,637	22,067	27,905
Number of generating units[a]	170	240	340
Capital investment, 1990-2020 (Million 1988 US$)	14,134	20,394	28,947
Average specific investment (1988 US$/kW)	1,355	1,372	1,398
Cost of electricity production in 2020			
Average system cost (c/kWh)	3.2	3.5	3.7
Marginal cost of new supply (c/kWh)	4.3	4.3	4.3
Employment			
New jobs created, 1990-2020[b]	215,796	268,982	341,536
Investment (1988 US$) per job	65,500	75,819	84,756
New land area required in NE region			
Total (km^2)[c]	17,685	39,078	68,486
Percent of total NE area	1.1%	2.5%	4.4%

(a) For each demand growth rate, the number of sites associated with electricity from hydro and sugarcane are 14 and 120, respectively. The latter is an estimate. The number of plantation wood-fired units is estimated assuming a unit size of 60 MW. (In practice individual units might be clustered into modules of 4 or 5 units each.)

(b) For each demand growth rate, the number of jobs associated with producing electricity from hydro and sugarcane are 5864 and 174444, respectively. Also included in the total number of jobs are those associated with establishing and maintaining plantations during the period 2015 to 2020. Plantations established during this period would not be harvested until after 2020.

(c) All area is wood plantation, except for 447 km^2 flooded at hydroelectric sites. Only 70% of the plantation area would be active plantation. The balance would be left in "natural" form. The plantation area includes a substantial fraction that would be established between 2015 and 2020, but which would only be harvested in the period 2021 to 2026.

6. Toward Sustainable, Utility-Scale Biomass Electricity in Northeast Brazil

Based on the scenario presented above, the potential for biomass to play a role in the electricity sector of Northeast Brazil beginning at the turn of the century is significant. However, neither the biomass production infrastructure nor the advanced gas-turbine conversion technologies included in the above scenario analysis are developed today, and there are technical, economic, environmental, and other questions that remain to be answered before advanced, utility-scale biomass systems can realistically be counted on to supply electricity. Efforts are ongoing in Brazil and elsewhere to address such issues and thereby provide the basis for realizing a major new role for biomass in the electricity sector.

6.1. Biomass Production for Energy

In the production of biomass energy from sugarcane or from tree plantations, perhaps the most important uncertainties relate to environmental and ecological sustainability.

In the case of sugarcane, a key issue is the impact of removing some of the tops and leaves from the field. No studies have yet been completed to determine the fraction of the tops and leaves that should be left on the field. In tropical regions, the primary consideration is protection of the soil from raindrop impact and subsequent topsoil erosion. One estimate of the fraction of cane tops and leaves that should remain on the field is 25% (Santo, 1991). (We have assumed that about 50% would be left on the field -- see Table 4.) A key social issue is whether the recovery of tops and leaves can be accomplished in ways that helps ameliorate, rather than exacerbate, the highly seasonal nature of employment in the sugarcane industries today.

In the case of wood, older Brazilian plantations (30+ years) have shown that it is possible to maintain and improve on high wood growth rates. More recent efforts have demonstrated that successful plantations can be established on formerly deforested or otherwise degraded lands (Betters et al., 1991; Hall et al., 1992). The longer-term challenge is to ensure that plantations can be designed to be ecologically sustainable. This is a particularly important consideration for plantations that would be established on the scales envisioned in the scenario presented above.

Because returns from plantation investments are not realized until well into the future, there is some inbuilt economic incentive to ensure that long-term environmentally sustainable strategies are fully implemented from the outset. Many of the companies operating plantations in Brazil today appear to appreciate this perspective and are pursuing practices to help insure sustainability (Betters et al., 1991). Many companies in Brazil maintain site-directed research, development, and monitoring efforts relating to the impacts of species selection, pesticide and fertilizer application, water retention, biodiversity levels, and other factors on overall productivity.

While knowledge is far from complete, some interesting findings have already emerged. For example, leaving one-quarter to one-third of the estate area in its natural state helps to minimize pesticide use as a result of the biodiversity (primarily birds) that reside in the naturally vegetated areas. Interconnecting corridors of natural vegetation help ensure that the flora and fauna do not become genetically isolatated and thereby susceptible to weakening by inbreeding (Rosillo-Calle et al., 1992).

Another interesting finding is that the use of mixed-species may help to ensure an optimal nutrient status in the plantation and thus reduce or completely eliminate the need for artificial fertilization. Studies in Hawaii (DeBell et al., 1989), Brazil (de Jesus et al., 1992), and India (Shailaja et al, 1991) using *Eucalyptus* of various species intercropped with nitrogen-fixing species such as *Leucena* or *Albizia* have shown that it is possible to maintain both the yields and nitrogen status of the soils without using nitrogen fertilisers, or with much reduced fertiliser inputs (de Barros and de Novais, 1990).

Much of the plantation R&D efforts to date have focussed on the production of highly uniform feedstocks for industrial processing. Because energy applications are less sensitive to feedstock uniformity, energy plantations may offer greater opportunity for use of mixed species and/or native species. Native species may be ecologically preferable, but little work has been done on understanding their energy potential.

6.2. Conversion Technology

While biomass-gasifier/gas turbine power generating technology is not commercially established today, if ongoing development efforts are successful, it will be commercially ready before the year 2000. Three projects currently ongoing outside of Brazil are aimed at demonstrating the technical and economic feasibility of the technology. Ahlstrom, a Finnish biomass gasifier manufacturer, in a joint venture with Sydkraft, the second largest electric utility in Sweden, will complete construction of a 6 MW (electric) biomass-gasifier/GTCC district heating cogeneration plant in Varnamo, Sweden by early 1993 (Jonsson, 1992). Vattenfall, Sweden's largest utility, is developing plans for a large-scale (less than 50 MW_e) GTCC district heating cogeneration plant, using a gasifier under development by Tampella, a Finnish forest-products company (Lindman, 1992). The Institute of Gas Technology in the US is building a pressurized gasification system in Hawaii to demonstrate the gasification of bagasse as the first step toward demonstration of an integrated gasifier/gas turbine system (Trenka et al., 1991).

A fourth project is based in Northeast Brazil, where a 25 to 30 MW (electric) stand-alone biomass-gasifier/GTCC power plant will be demonstrated. CHESF is taking a leadership role in the project within a consortium of participating companies that includes Electrobras (CHESF's parent company that has overall responsibility for Brazil's power sector), Companhia Vale do Rio Doce (a major company in the iron, steel, and forestry sectors), Fundacao de Ciencia e Tecnologia do Rio Grande do Sul (CIENTEC) (an R&D institution with extensive experience in gasification), and Shell Brasil (a subsidiary of the Shell International Petroleum Company). European and US based companies are participating as equipment developers and suppliers. The demonstration plant will be sited in Bahia, with fuel provided from a standing *Eucalyptus* plantation. The project is now in the engineering design and equipment development phase, which will be completed by June 1994. This phase is being supported by a $7 million grant from the Global Environment Facility. An additional $23 million grant, contingent on successful completion of the current phase, will help fund subsequent construction of the plant. Plant testing is expected to be completed by the end of 1997, after which the plant will be placed on line as a commercial unit within the CHESF system.

7. CONCLUSIONS

We have presented here an assessment of the prospects for the development of significant, sustainable, biomass-based power supply in Northeast Brazil. There are many uncertainties in our analysis, but we have attempted to be conservative in our assumptions. With a reasonable commitment from government, utilities, industry, and relevant R&D organizations, and the support of the population in general for the establishment of a significant bio-electricity component to the power system in the Northeast, it appears that the BIOMASS scenario we have described here, or some variant thereof, should be within grasp. As summarized in Table 18, compared to a business-as-usual expansion of the hydro supply system, a biomass-intensive future development of the Northeast's power system would entail lower investment costs to supply the same amount of electricity, lower average electricity costs, many more jobs in rural areas, and it would help minimize the need to exploit environmentally-sensitive hydro resources in the Amazon region. Bioenergy plantations may have still greater environmental benefit, e.g. if they involve the restoration in ecologically sustainable ways of deforested or otherwise degraded lands.

The bioenergy-intensive scenario we have described presents institutional, as well as technological challenges. Tariff reform would be needed, e.g. to insure that industrial cogenerators with excess electricity available could sell it to utilities for a fair price. New industrial partnerships and the regulatory reform needed to encourage these might be required, e.g. to allow utilities to form joint ventures with forest products companies that have expertise in plantation production technology. A new generation of individuals would need to be trained to establish and operate the new infrastructure components (sugarcane tops/leaves production, wood plantations, gas turbine power plants, etc.)

While the technological and institutional challenges are large, the present hydro-intensive approach to expanding electricity supply in Brazil shows clear signs of exhaustion; a new approach is needed. As in many developing countries, the utility system in Brazil is financially stressed and highly politicized due to the massive concentration of investments at single sites. The entreprenurial spirit that marked the early days of the utility business in Brazil has vanished, and a lack of motivation is evident throughout the utility system. On the other hand the huge investments already made, the significant infrastructure already in place, and the enormous human resources developed over the years are assets that cannot be wasted. Biomass-intensive development of the utility system might help ease the financial and political stresses in the system and would offer new challenges that might invigorate the electric utility industry and society in general.

8. ACKNOWLEDGEMENTS

For support in the completion of this work, one of the authors (AEC) thanks the Companhia Hidroeletrica do Sao Francisco. For financial support of his participation in this work, EDL thanks the Air and Energy Engineering Research Laboratory and the Office of Policy, Planning and Evaluation of the US Environmental Protection Agency, the Office of Energy and Infrastructure of the US Agency for International Development, the Bioenergy Systems and Technology Program of the Winrock International Institute for Agricultural Development, and the Rockefeller, Geraldine R. Dodge, W. Alton Jones, Merck, and New Land Foundations. The authors also thank the organizations that contributed data and information to the study. Corporate contributors include Divisao de Planejamento de Geracao do Departamento de Planejamento de Geracao e Mercado do Companhia Hidroeletrica do Sao Francisco, Companhia Agricola Florestal Santa Barbara, Florestal Acesita, Copene Energetica, and Cimento Nassau; research insitutes include Escola Superior de Agricultura Luiz de Queiroz (Universidade de Sao Paulo), Instituto de Pesquisas e Esudos Florestais, and Centro de Pesquisa Agropecuaria para o Tropico Semi-Arido and Centro Nacional de Florestas and their parent institute, Empresa Brasileira de Pesquisa Agropecuaria.

9. REFERENCES

ABRACAVE (Charcoal Producers Association), *Statistical Yearbook*, Belo Horizonte, Minas Gerais, Brazil, 1991 and 1992.

A.G. Alexander, *The Energy Cane Alternative*, Sugar Series 6, Elsevier, Oxford, 1985.

Banco do Nordeste, *Incentivos Fiscais do Nordeste: Evaluacao e Suggecao Improvemento*, SUDENE, Recife, 1990.

M. Bazett, *The Need for Industrial Wood Plantations*, Study No. 3 in the Tree Plantation Review, Non-Traditional Business Group, Shell International Petroleum Company, London, 1992.

D.R. Betters, L.L. Wright, and L. Couto, "Short Rotation Woody Crop Plantations in Brazil and the United States," *Biomass and Bioenergy*, 1(6), pp. 305-316, 1991.

E. Campinhos Jr. and Y.K. Ikemori, "Selection and Management of the Basic Population *Eucalyptus Grandis* and *E. Urophylla* established at Aracruz for the Long Term Breeding Programme," in *Breeding Tropical Trees: Population Structure and Genetic Improvement Strategies in Clonal and Seedling Forestry*, Gibson, Griffin, and Matheson (eds.), Oxford Forestry Institute (Oxford, UK) and Winrock International (Arlington, Virginia, USA), 1989.

A.E. Carpentieri, *An Assessment of Sustainable Bioenergy in Brazil: National Overview and Case Study for the Northeast*, PU/CEES Working Paper No. 119, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, April 1991.

CHESF, *Estudos de Florestament no Semiarido Nordestino*, Divisao de Projetos de Fontes Alternativas, Recife, Nov., 1985.

CHESF, *Inventario e Tecnologia Biomassa Florestal Madeira*, Recife, 1987.

CHESF, "Florestal Biomass Program (English Summary)," Engineering Department, Recife, February 1989.

CHESF, *Biomassa Florestal para Geracao de Energia Eletrica*, Recife, Nov. 1990.

CHESF, *Biomassa Florestal: Uma Alternativa Para Gerecao de Electricidade na Regiao Nordeste do Brasil (Forest Biomass: An Alternative for Power Generation in the Northeast of Brazil)*, Recife, Aug., 1991a.

CHESF, *Energia Eletrica: O Futuro Apos Xingo*, Divisao de Planejamento e Operacao, Recife, December, 1991b.

Copersucar, *Proalcool: Fundamentos e Perspectivas*, Piracicaba, Sept. 1989.

Council of Economic Advisors, *Economic Indicators*, US Government Printing Office, Washington, DC, June 1992.

J. Davidson, *Bioenergy Tree Plantations in the Tropics: Ecological Implications and Impacts*, Commission on Ecology Paper No. 12, International Union for the Conservation of Nature and Natural Resources, 1987.
N.F. de Barros and T.F. de Novais (eds), *Relacao Solo-Eucalipto (Soil-Eucalyptus Relationships)*, Editora Folha de Vicosa, Mannesmann, Vicosa, Minas Gerais, Brazil, 1990.

D.S. DeBell, C.D. Whitesell, and T.H. Schubert, "Using N_2-Fixing Albizia to Increase Growth of Eucalyptus Plantations in Hawaii," *Forest Science*, 25:64-75, 1989.

R.M. de Jesus, "The Need for Reforestation," paper presented at the US Environmental Protection Agency-sponsored Workshop on Large-Scale Reforestation, Corvallis, Oregon, 1990.

R.M. de Jesus, G.B.N. Dias, E.M. Cardoso, "Eucalyptus/Leucaena Mixture Experiment- Growth and Yields," *Biomass and Bioenergy*, Pergamon, London, 1992 (in press).

J. Goldemberg, L.C. Monaco, and I.C. Macedo, "The Brazilian Fuel-Alcohol Program," in *Renewable Energy: Sources for Fuels and Electricity*, T.B. Johansson, H. Kelly, A.K.N. Reddy, R.H. Williams (eds), Island Press, Washington, D.C., 1992.

D.O. Hall, H. Mynick, and R.H. Williams, "Alternative Roles for Biomass in Coping with Greenhouse Warming," *Science and Global Security*, Vol. 2, pp. 113-151, 1991.

D.O. Hall, F. Rosillo-Calle, R.H. Williams, and J. Woods, "Biomass For Energy: Supply Prospects," in *Renewable Energy: Sources for Fuels and Electricity*, T.B. Johansson, H. Kelly, A.K.N. Reddy, R.H. Williams (eds), Island Press, Washington, D.C., 1992.

R. Howe and P. Sreesangkom, *Cost and Performance of Equipment for Baling Sugar Cane Tops and Leaves*, Winrock International Institute for Agricultural Development, Washington, DC, 1990.

IBGE (Fundacao Instituto Brasileiro de Geografia e Estatistica), *Agricultural Land Use Census*, Rio de Janeiro, 1985.

IBGE (Fundacao Instituto Brasileiro de Geografia e Estatistica), *Anuario Estatistico do Brasil,* Rio de Janeiro, 1977, 1981, 1990 and 1991.

O. Jonsson, EnerChem AB, Malmo, Sweden, personal communication, April 30, 1992.

E.D. Larson, *A Developing-Country Oriented Assessment of Technologies and Costs for Producing Gases, Liquids, and Electricity from Biomass*" contractors report to the Office of Technology Assessment, US Congress, Washington, DC, Sept., 1991.

E.D. Larson, P. Svenningsson, I. Bjerle, "Biomass Gasification for Gas Turbine Power Generation," *Electricity: Efficient End-Use and Generating Technologies and Their Planning Implications,* Johansson, Bodlund, Williams (eds), Lund University Press, Lund, Sweden, 1989.

E.D. Larson and R.H. Williams, "Steam-Injected Gas Turbines," *J. of Engineering for Gas Turbines and Power*, Vol. 109, No. 1, 1986.

E.D. Larson, R.H. Williams, J.M. Ogden, and M. Hylton, "Biomass-Gasifier Steam-IUnjected Gas Turbine Cogeneration for the Cane Sugar Industry," *Energy from Biomass and Wastes XIV*, Institute of Gas Technology, Chicago, 1991.

N. Lindman (Vattenfall, AB), "Biomass Based Combined Cycles," in *Advances in Biomass Thermochemical Conversion*, Elsevier, 1992 (forthcoming).

F. Rosillo-Calle, P. Furtado, and D.O. Hall, "Brazil Charcoal: A Case Study for Sustainable Production and Use," published by the Biomass Users Network, 1992.

R. Shailaja, N.H. Ravindranath, and K.S. Jagadish, "Experiments in Mixed Species Foresty," *Proc. Annual Symposium of Bioenergy Society of India*, New Delhi, 1991.

A. Strehler and W. Stutzle, "Biomass Residues," in D.O. Hall and R.P. Overend (eds), *Biomass: Regenerable Energy*, Wiley, Chichester, UK, 1987.

A.R. Trenka, C.M. Kinoshita, P.K. Takahashi, C. Caldwell, R. Kwok, M. Onischak, and S.P. Babu, "Demonstration Plant for Pressurized Gasification of Biomass Feedstocks," in *Energy from Biomass and Wastes XV*, D.L. Klass (ed), Institute of Gas Technology, Chicago, 1991.

R.H. Williams and E.D. Larson, "Expanding Roles for Gas Turbines in Power Generation," in *Electricity: Efficient End-Use and Generating Technologies and Their Planning Implications,* Johansson, Bodlund, Williams (eds), Lund University Press, Lund, Sweden, 1989.

R.H. Williams and E.D. Larson, "Advanced Gasification-Based Biomass Power Generation," in *Renewable Energy: Sources for Fuels and Electricity*, Johansson, Kelly, Reddy, and Williams (eds), Island Press, Washington, DC, 1992.