Developing countries
& Global climate change

Electric Power Options in Brazil

Prepared for the Pew Center on Global Climate Change

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Contents

Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

Brazil is the fifth largest country in the world and its economy is roughly equal to that of all other South American countries combined. Yet, its greenhouse gas emissions are less than one-third of the continent's total due to the dominant role of hydropower. Total energy consumption is less than one-tenth the level in the United States and per capita carbon emissions are just 0.5 tons, compared to approximately 1.0 ton in Argentina and Mexico.

Brazil is already considered an environmental leader among developing countries and plays a significant role in the international climate change debate. Whether it is able to stay on this path will depend in part on its energy choices over the next fifteen years. This report describes the context for new power sector investments and presents three alternative policy scenarios for 2015. The report finds that:

- Construction of new hydroelectric plants is increasingly expensive and controversial due to social and environmental impacts. As a result, many new investors may favor natural gas-fired combined-cycle plants. Under a business-as-usual trajectory, carbon dioxide emissions will grow from 3.4 million tons in 1995 to 14.5 million tons in 2015, mainly due to this shift to natural gas.

- Further tightening of local environmental regulations and adoption of renewable energy policies could reduce carbon dioxide and sulfur dioxide emissions by 82 percent and 75 percent, respectively, by 2015 compared to the baseline scenario, at little additional cost.

- Creating a carbon-free power sector would require an additional $25 billion in cumulative costs by 2015 — about 15 percent more than the business-as-usual scenario — and would expand the use of renewable energy resources.

- Wind power potential could be harnessed — increasing from zero to 2 percent of total installed capacity by 2015 — depending on the extent of government subsidies.

Developing Countries and Global Climate Change: Electric Power Options in Brazil is the fifth of a series commissioned by the Pew Center on Global Climate Change to examine the electric power sector in developing countries, including four other case studies of Korea, India, China, and Argentina.

The Pew Center was established in 1998 by the Pew Charitable Trusts to bring a new cooperative approach and critical scientific, economic, and technological expertise to the global climate change debate. We believe that climate change is serious business, and only through a better understanding of circumstances in individual countries can we hope to arrive at a serious response.

Executive Summary

Brazil generates over 90 percent of its electricity by capturing the energy in falling water. Per capita carbon emissions in Brazil are less than half the world average, largely because of the country's heavy reliance on hydropower, which produces few greenhouse gas emissions. Many of the country's new power plants, however, will likely use natural gas since many investors view hydroelectric plants as increasingly costly, controversial, and risky.

This study analyzes the options for meeting power demand in the Brazilian power sector through 2015. Meeting this demand at least-cost — including the estimated costs of environmental impacts — is a topic of great concern for decision-makers in government and industry. The electric power choices Brazil makes may influence the global response to climate change out of proportion to its emissions, as Brazil is considered an environmental leader among developing countries.

Current reforms in the power sector have been designed mainly to cut costs by introducing competition in electricity generation. Other objectives include reducing government investment in power plant construction and the risk of electricity shortages. These reforms have catalyzed institutional changes in Brazil: privatization, elimination of tariff equalization across regions, and the introduction of supply contracts between power generation and distribution utilities.

The authors begin with a brief review of Brazil's economic and energy situation, then turn to a detailed account of the nation's electric power sector. The report presents results of regional electric power demand forecasts through 2015 and assessments of available energy resources and technologies. An analysis using a linear programming model determines the least-costly combinations of power supply technologies that meet projected power demand.

Three policy cases were devised to test economic and environmental policy measures against a baseline: advanced technologies, local environmental control, and carbon elimination. Least-cost modeling simulated these scenarios through changes in emissions fees and caps, costs for advanced technologies, demand-side efficiency, and clean energy supplies.

The authors conclude that, without alternative policies, new additions to Brazil's electric power sector will shift rapidly from hydroelectricity to combined-cycle natural gas plants. Greenhouse gas emissions will thus increase rapidly, although the absolute quantities will remain relatively low. While combined-cycle natural gas plants generate power with 60 percent less carbon dioxide emissions than coal units, greenhouse gas emissions will still rise rapidly as the gas plants replace hydropower facilities that are nearly carbon-free. Specifically, the scenarios produced the following results:

Baseline Scenario. This scenario assumes that institutional reform such as privatization and increased competition among generators is successfully implemented over the coming decade. The installed capacity grows from 56 gigawatts in 1995 to 94 gigawatts in 2015, an increase of 68 percent. Natural gas plants increase from essentially zero to 11 percent of installed capacity over the period of analysis. Energy efficiency and cogeneration play important roles in limiting an even greater reliance on fossil fuel power generation. The total cost of meeting demand is $183 billion,[1] which includes capital, fuel, and operation and maintenance costs. Carbon dioxide emissions rise more than four-fold from 3.4 million tons of carbon in 1995 to 14.5 million tons in 2015. However, the intensity of CO_2 emissions in Brazil remains low, even in 2015, as hydropower still accounts for 74 percent of total generation. Sulfur dioxide and particulate emissions grow proportionately with power generation, while nitrogen oxides increase five-fold to reflect the greater use of natural gas in power generation turbines.

Advanced Technology Scenario. The advanced technology scenario simulates capital cost reductions for power plant equipment due to technological progress driven by government incentives. Environmental costs are also at least partially accounted for in the least-cost analysis by including some of the external costs of emissions, hydropower construction, and nuclear decommissioning that are normally ignored. Wind power increases from zero to almost 2 percent of total installed capacity by 2015 due to the environmental fees imposed on fossil-fuel use. The total cost of this scenario is $181 billion, 1.6 percent less than the baseline, mainly due to the cheaper costs of building and operating combined-cycle power plants in the later years. This figure does not include the research, development, and deployment costs needed to improve technologies. Carbon dioxide emissions drop slightly from the baseline, reaching 13.3 million tons of carbon in 2015. Sulfur dioxide emissions decline by approximately 50 percent due to the elimination of diesel generators after 2005.

Local Environmental Control Scenario. In this scenario, renewable energy policies and the use of higher environmental externalities influence the technologies employed. The environmental costs of pollution are assessed at a higher value than in the technology scenario, and cost reductions for cleaner, advanced technologies are also assumed. Hydropower plays a larger role in this scenario, rising to over 88 percent of total installed capacity. The environmental and social impacts of expanding hydroelectric power production this much are difficult to estimate, but could be significant. Biomass capacity rises from 2 percent in the 2015 baseline case to 5 percent. The cost of this scenario is $179 billion. Carbon dioxide emissions drop from 3.4 million tons of carbon in 1995 to 2.6 million tons in 2015. Sulfur dioxide emissions decline substantially, while particulate emissions increase due the growth in biomass combustion for power generation.

Carbon Elimination Scenario. In the carbon elimination scenario, Brazil installs electric power generation technologies that produce no net carbon dioxide emissions and only minor impacts on watersheds and landscapes. Installed capacity in 2015 reaches 97 gigawatts, and hydropower continues to account for over 80 percent of installed capacity. Renewable energies account for 97 percent of power generation in 2015, with biomass accounting for over 16 percent. The remaining 3 percent is generated from existing nuclear power plants. The total cost of the expansion is $208 billion, 14 percent above the baseline scenario. Carbon emissions cease and sulfur dioxide emissions drop, but particulate emissions rise five-fold due to the heavy reliance on biomass.

Conclusions

Brazilian power supply will continue to rise at appreciable rates over the next two decades regardless of the country's current economic difficulties. Reforms under way in the power sector, however, will greatly influence how power demand is met and the emissions that result. Hydropower will continue to play a dominant role through 2015, although its relative share will most likely decrease.

Carbon emissions more than quadruple in the baseline scenario to 14.5 million tons, but remain extremely low in absolute terms. (For comparison, the U.S. power industry released approximately 550 million tons of carbon dioxide in 1998.[2]) This output is equivalent to the emissions from 10 large coal-fired power plants. Biomass and wind power might play a larger role in Brazil's power future if the government focuses on developing advanced technologies and accounts for at least some of the costs to the environment. Coal-based technologies are not competitive with other forms of power generation, allowing Brazil to largely avoid the tradeoff between improving the quality of the local environment and reducing global greenhouse gas emissions.

In the local environmental control and carbon elimination scenarios, there is a strong interdependence between electricity generation based on sugar cane bagasse and ethyl alcohol production for automotive use. By accounting for the environmental impacts of local pollutants or restricting power generation options to those with no carbon dioxide emissions, sugar cane bagasse becomes feasible, making it the power generation technological option that is most widely used in both scenarios after hydropower. This indicates that Brazil has the potential to service the electricity market without carbon emissions if the market or the international community can support the 14 percent higher costs.

In all four scenarios, energy efficiency and cogeneration play an important role in the least-cost power solution. Saving electricity through increased efficiency offsets the need for new supply and has enormous potential in Brazil's industrial sector. Efficiency also reduces the environmental burden associated with electricity production and transmission (most likely via natural gas combined-cycle plants) without compromising the quality of services that end users demand.

Carbon dioxide emissions from Brazil's power sector will remain low in absolute terms over the next two decades. Brazil appears able to play a unique role within the context of the UN Framework Convention on Climate Change by fostering economic growth that does not sacrifice local or global environmental quality. Achieving cleaner development would serve as a powerful example for other developing countries.

I. The Brazilian Energy Picture

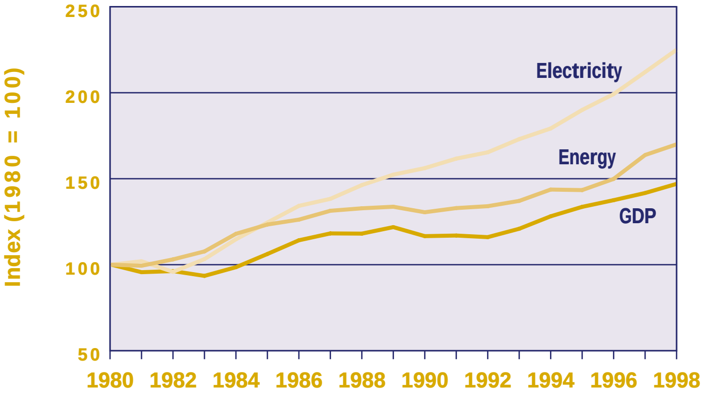
A. The Role of Energy in Brazil's Economy

Brazil generates over 90 percent of its electricity by capturing the energy in falling water. Per capita carbon emissions in Brazil are less than half the world average, largely because of this heavy reliance on hydropower, which produces few greenhouse gas emissions.[3] A significant portion of the country's new power plants, however, will likely use natural gas since hydropower plants are increasingly expensive, controversial, economically risky, and slow to come on-line. Brazil's economy is also characterized by heavy dependence on electricity-intensive industries and fairly fixed demand for power despite the economic situation (inelastic demand).

Brazil's economy has suffered bouts of hyperinflation and recession over the past 20 years. Gross domestic product (GDP) has expanded at an average yearly rate of 2.1 percent since 1980, mainly due to stagnant growth from 1987 to 1993. (See Figure 1.) Financial panic spread to São Paulo in late 1998 and early 1999 when international investors withdrew capital *en masse*, fearing that reforms were proceeding too slowly, leading to a collapse of the *real*, Brazil's national currency.[4] Interest rates and inflation have since stabilized, however, and the economy looks ready to return to more rapid growth in 2000.

Figure 1

Brazilian **Economic and Energy Growth** 1980-1998



Source: Ministério das Minas e Energia – Brasil. 1998. *Balanço Energético Nacional.* Brasília: MME.

Energy demand grew rapidly during the 1970s, but slowed considerably over the past 20 years. Still, growth in primary energy and electricity demand grew much faster than the economy. The income elasticity of demand for energy (the ratio of growth in energy consumption to growth in the economy) averaged 1.5 between 1980 and 1998, while the elasticity of electricity demand was 2.7. Both values are higher than those typically found in other industrializing countries, meaning that each additional dollar of GDP in Brazil requires more energy to produce.[5]

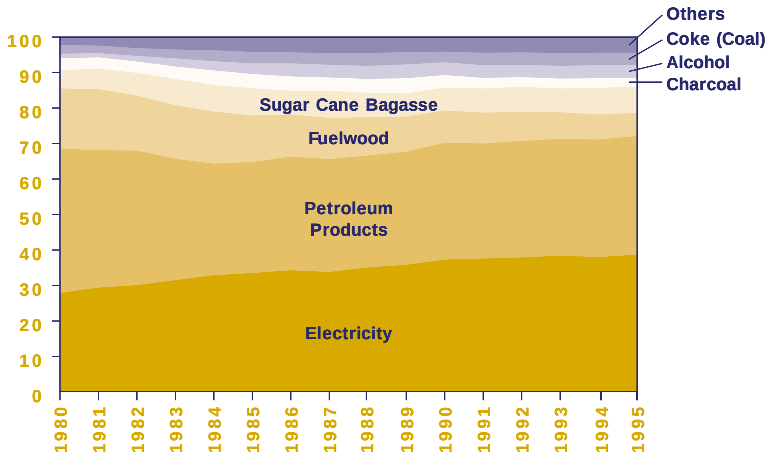
Total energy consumption in 1998 reached 10 exajoules, an increase of over 34 percent in one decade. Brazilians consume roughly three times as much energy per capita as people in India, slightly more than the average Chinese, but only half as much as Argentinians.[6] Electricity consumption rose at an average annual rate of 7.9 percent from 1970 through 1997, increasing its share of total energy consumption from 16 to 39 percent.[7]

Brazil imports approximately one-third of its petroleum due to insufficient domestic production. Sophisticated offshore drilling techniques have kept the import gap from widening even further. Rapid reforms are now transforming the country's petroleum sector and giving the private sector an increasingly important role in developing new petroleum resources.

Renewable energy sources such as hydropower, fuel wood, and sugar cane-based products play leading roles in the Brazilian energy sector, accounting for nearly 60 percent of total energy demand. (See Figure 2.) Brazil uses bagasse — the residual product from sugar cane processing — and alcohol fuel produced from sugar cane to offset the need to import tens of millions of tons of crude oil and petroleum products each year. No other large country relies on renewable energy to such a degree.

Figure 2

Energy Consumption as a Percent of Total



Note: Note that hydropower accounts for over 90 percent of electricity. "Others" includes natural gas, steam coal, and coke gas.

Source: Ministério das Minas e Energia – Brasil. 1998. *Balanço Energético Nacional*. Brasília: MME.

Coal, nuclear power, and natural gas play minor roles in Brazil. Domestic coal resources have high ash and sulfur content, so most of the coal used in steel production is imported. Brazil's second nuclear power plant will come on-line in 2000 and a third is under construction, but high costs and public opposition have prevented nuclear power from playing a larger role. Brazil, like China, has reexamined natural gas and has implemented policies to dramatically increase gas use. A new pipeline from Bolivia was recently completed and several others from Argentina are under discussion. Natural gas is expected to account for much of the country's future fossil-powered electricity supply.

Brazilian industrial policy promoted exports of energy-intensive steel, aluminum, and iron-alloy products in the 1970s and 1980s. As a result, industry's share of final energy consumption rose from 31 to 40 percent between 1975 and 1997. Growth of energy use in the residential sector declined slowly during the 1990s as liquefied petroleum gas (LPG) replaced the much less efficient firewood and more households became power customers. The commercial and residential sectors together account for just over 20 percent of all consumption, equal to energy consumption in the transport sector. The energy and public sectors account for the remaining 15 percent.[8]

B. Supply and Demand in the Power Sector

Brazil's installed electricity capacity expanded rapidly between 1970 and 1997, rising from just over 10 gigawatts to 60 gigawatts.[9] Hydropower has accounted for a continuously growing share of total capacity: 84 percent (8.7 gigawatts) in 1970, 88 percent (27 gigawatts) in 1980, and 91 percent (54.2 gigawatts) in 1997.[10] Power generation capacity includes partial control of the world's largest hydroelectric plant. Itaipu is jointly owned and operated by Brazil and Paraguy and has 12,600 megawatts of capacity. For comparison, the Grand Coulee dam is the largest hydroelectric plant in the United States with about 6,500 megawatts of capacity.

Table 1

Electricity Generation in Brazil, 1990-1997 (terawatt-hours)

	1990	1997
Total Generation	223	308
Hydropower	207	279
Diesel and Residual Fuel Oil	5	9
Coal	3	6
Other Sources	4	6
Sugar Cane Bagasse	2	4
Nuclear	2	3
Natural Gas	1	1

Note: Does not include on-site or self-production.

Source: Ministério das Minas e Energia – Brasil. 1998. *Balanço Energético Nacional.* Brasília: MME.

Hydropower generation accounts for about 94 percent of total electricity production, with diesel, residual oil, coal, and assorted biomass plants providing the remainder. (See Table 1.) Brazilian hydropower plants have relatively high capacity factors due to consistent rainfall and damning capacity. (The capacity factor is the ratio of power produced by a generating unit to the maximum amount of power that could have been produced during a given time period). Non-hydropower generation is used primarily to support the grid during the dry season and in remote areas not connected to the grid.

Electricity consumption has doubled since 1980, reaching 274 terawatt-hours in 1997. (See Table 2.) Power demand in the industrial sector rose steeply during the 1970s, reaching 54 percent of total electricity consumption by 1980. However, growth rates have since slowed, averaging only 5 percent per year, compared to over 14 percent during the 1970s. The 1990s saw the restructuring of Brazil's industrial sector. Slower expansion of electricity-intensive sectors resulted in an average annual growth of 2.9 percent in electricity consumption.[11]

Table 2

Electricity Consumption by Sector 1970-1997 (terawatt-hours)

	1970	1980	1990	1997	Growth Rate 1970-80 (Percent)	Growth Rate 1980-90 (Percent)	Growth Rate GR 1990-97 (Percent)
Industrial	16	62	100	122	14	5	3
Residential	8	23	48	74	11	8	6
Commercial	5	14	24	38	10	6	7
Government	6	14	23	30	9	5	4
Agricultural	0.3	2	7	10	20	13	6
Total	36	114	201	274	12	6	5

Note: Does not include on-site or self-production. Values are rounded to the nearest whole number.

Source: Eletrobrás. 1998. *Plano Decenal de Expansão – 1998-2007.* Rio de Janeiro: Eletrobrás.

The industrial sector still accounts for 45 percent of the country's electricity use, largely as a result of the electricity-intensive metallurgical and chemical sectors. Aluminum, iron, cement, petrochemical, and pulp and paper manufacturers account for approximately 25 percent of Brazil's total power consumption.[12] Power demand in the agricultural and commercial sectors has also grown rapidly over the past two decades. During the 1990s, electricity use in the commercial sector expanded due to longer business hours, new recreation facilities, increased tourism, and the construction of numerous malls and shopping centers that impose relatively high demands during peak periods.

Brazilians consume an average of 1,790 kilowatt-hours per person each year, about one seventh of the average consumption in the United States, but demand varies considerably with location. The country is typically divided into five regions to classify electricity characteristics. Most electricity is consumed in the industrialized southeast region, which includes São Paulo and Rio de Janeiro. (See Table 3.) The most rapid growth, however, has occurred in the previously undeveloped north and midwest.

Table 3

Electricity Consumption by Region

1970-1997 (terawatt-hours)

	1970	1980	1990	1997	Growth Rate 1970-80 (Percent)	Growth Rate 1980-90 (Percent)	Growth Rate 1990-97 (Percent)
North	0	2	9	14	17	17	7
Northeast	3	14	31	43	16	8	4
Southeast	28	81	124	161	11	4	4
South	4	14	28	43	15	7	6
Midwest	1	3	8	14	19	10	7
Total	36	114	201	274	12	6	5

Note: Does not include on-site or self-production. Rounding off may result in totals other than 100 percent.

Source: Eletrobrás. 1998. *Plano Decenal de Expansão – 1998-2007.* Rio de Janeiro: Eletrobrás.

Average electricity consumption per household in Brazil is increasing steadily. From 1970 through 1997, the number of households rose from 6.8 to 35.3 million while demand per household approximately doubled in most regions. In 1997, household use ranged from a low of 111 kilowatt-hours per month in the northeast to over 200 kilowatt-hours per month in the southeast. (See Table 4.) The high average growth rate of 6.3 percent over the period — well above Brazil's demographic growth rate — may rise further. Because of regional disparities, there is still room for growth in the number of residential consumers.[13]

Table 4

Average Consumption by Household

	Kilowatt-hours/household/month 1970	1980	1990	1997
North	84	143	158	165
Northeast	74	88	98	111
Southeast	116	157	179	204
South	76	116	152	173
Midwest	103	136	165	185
Total	103	135	155	175

Source: Ministério das Minas e Energia – Brasil. 1998. *Balanço Energético Nacional.* Brasília: MME.

Heavy reliance on hydropower also results in striking seasonal variation — not to be confused with consistency — in power availability. Transmission grids thus play an important role in helping balance supply and demand. The largest interconnected power transmission system includes the southeast, south, and midwest regions with an installed capacity of nearly 43 gigawatts as of January 1998. The system includes Itaipu and 190 other hydropower plants. The hydropower plants in this grid account for 92 percent of its total capacity. The system also has a potential of about 39 gigawatts, already inventoried, for new hydropower ventures. Twenty four thermal plants account for the remaining 8 percent of capacity. These plants include coal-fired power plants with nearly 3 gigawatts of capacity, and the only nuclear power plant currently operating in Brazil: Angra I, which has 657 megawatts of installed capacity.[14]

Another grid system connects the north and northeast regions with an installed capacity approaching 15 gigawatts. This system has 17 hydropower plants accounting for 98 percent of the grid's total installed capacity and three small thermal power plants. It also has hydropower potential inventoried at 58 gigawatts.

Losses due to electrical resistance and theft in these two transmission grid systems are significant. The amount of power lost has risen slowly since 1980 from 13 to 13.7 percent in 1997 — a relatively high level.[15] Three reasons account for these high losses. First, Brazil is a very large country, over which extensive transmission and distribution networks inherently lose power. Second, hydropower generation frequently requires lengthy transmission systems because power plants are not always located close to consumption centers. Finally, commercial losses have been increasing over the past few years due to increased theft and illegal connections. These losses can be explained partly by social inequalities that result in relatively high electricity consumption by one portion of the populace.[16]

The remaining system includes small, independent grids that are fairly isolated, largely in the north. The installed capacity of the individual systems reached nearly 2 gigawatts at the start of 1998, 60 percent of which comes from thermal power plants (mostly diesel generators) and the rest from hydropower. Approximately 10 percent of Brazil's population is unconnected to the power grid.[17]

II. Current Dynamics

A. Evolution

The recent history of Brazil's power sector can be divided into five phases. The fiscal phase lasted from 1955 through 1964. The government laid the foundation for Eletrobrás, the federally owned holding company, which was established in 1961.[18] During the business phase from 1964 through 1974, electricity rates were updated and calculated to recover investment and operating costs.[19] The debt phase lasted from 1974 through 1979, when the economy was overshadowed by Brazil's foreign debt. During this period, the nation attempted to complete its industrialization cycle, encouraging the construction of huge hydropower complexes, including Itaipu. The crisis bottoming-out phase covered the 1980s, when expansion capacity flagged. About 30 percent of the properties, plants, and equipment of Eletrobrás was tied up in projects that had ground to a halt.[20] The current phase, from the 1990s on, is characterized by a series of reforms in the electric power sector. These reforms are designed mainly to boost competition, attract foreign and domestic funding to expand the electricity system, and reduce the risk of electricity shortfalls.

B. Reform

Brazil has reformed the electric power sector to reduce the likelihood of power shortages, lessen the need for state-sponsored investment, and provide incentives for cost reduction. Law 8.631 (1993) is the cornerstone of these reforms. (See Box 1.) The law:

- eliminated tariff equalization between regions, allowing power generation and distribution utilities to set tariffs according to operating costs;[21]
- abolished credits held by federal generation utilities with state distributors (cross-subsidies between state distributors); and,
- introduced supply contracts between power generation and distribution utilities.

Parallel to Law 8.631, the federal government launched an intensive privatization process in 1995 that focused particularly on distribution utilities and also on generation companies. Privatization of

Box 1

Main Characteristics of Brazil's Electric Power Sector Reforms

Segment	Main Modifications
Generation	• End of the public service system: all generation utilities become subject to the license system, with hydropower activities requiring water use concessions.
Transmission	• Regulatory approval of a code for planning, scheduling, dispatching, connecting, and using the system. • Regulatory definition of a transmission price. • Mandatory publication of investment plans to allow independent service providers to define opportunities for new generation connections with the transmission network.
Distribution	• Continuation of the concession system, with mandatory supplies to the captive market. • Division between network and marketing activities, with separate accounting systems and licenses for marketing activities (without distribution) by generation utilities wishing to supply consumers directly. • Restrictions on the ownership of power generation assets by distributors.

federal power generation is scheduled for completion in 2000. Privatization efforts include the individual systems in northern Brazil. Brazilian officials found that privatization offered a two-fold solution: it transfers the primary role of long-term financing from the public to private sector and allows state and federal governments to use cash proceeds from asset sales to pay down debt. Significant delays have occurred in the transfer of state-owned assets to the private sector, due to macroeconomic instability and lack of definition of initial transmission and generation prices. The reform has been relatively successful in privatizing distribution companies but has failed to attract private investment to expand generation capacity. If this expansion does occur, foreign investors are expected to provide most of the capital.

One of the foundations of Brazil's new regulations is the creation of a competitive, wholesale energy market. This market consists of four distinct regions that allow potential buyers and sellers of electricity to negotiate real-time, spot power prices. Also, with the creation of an independent system operator, electricity markets will have an independent dispatch authority without ties to a specific utility. Dispatch will be determined on a prioritized low-cost basis. Each generation unit will be dispatched into the system according to a marginal cost curve (lowest cost first) until demand is met, creating an incentive for efficiency and cost control. Nevertheless, the dispatch of thermal units will probably occur after that of hydropower units with good hydrological conditions. Furthermore, power prices for gas-fired plants may undergo cyclic instabilities as a major cost input for these plants is the price of gas, which is linked to the United States dollar. The spot price will be set by the last dispatched unit of any fuel type to meet existing demand.

Moreover, prior to privatization, the electric utility industry in Brazil was highly regulated. Generation assets were bundled with transmissions assets, electricity was supplied to distributors at a regulated tariff, and the distributors supplied final customers with electricity through a class-based tariff structure. The new model has created three semi-competitive business segments: (1) generation companies operate in an open marketplace, making both spot and contract sales to large purchasers (distributors and heavy users); (2) transmission companies guarantee open access to the grid and operate under a fixed tariff framework, allowing a regulated return on assets; and (3) distribution companies have both "free" customers (large users that have permission to purchase electricity from their choice of power providers at a market price) and captive customers (users that purchase from the distributor under regulated tariffs).

C. Power Pricing

Historically, Brazilian policies did not provide enough incentives for investors to build power plants. Until 1995, electricity tariffs were based on Law 5.655 (1971), which mandated tariffs that allowed for a minimum real return on investment of between 10 and 12 percent per annum. During the 1980s, Brazil's electric power sector was severely affected by anti-inflation policies that imposed tight controls on tariff levels. This resulted in an insufficient return from tariffs, with low remuneration rates for investments. Tariffs bottomed out in 1993 at an average of $36 per megawatt-hour for end users.[22]

Law 8.631 eliminated uniform electricity tariffs and called for each company to propose its own tariff structure based on the marginal cost of servicing each customer, reduced cross-subsidies, and guaranteed returns on investments. Since November 1995, electricity tariffs were readjusted and calibrated to conform to each power company's specific cost structure. The average supply tariff rose to $62 per megawatt-hour in 1994 (at 1999 prices), climbing to $72 per megawatt-hour in 1995.[23] Although electricity tariffs have already reached levels compatible with international standards, they are still

Table 5

Average Electricity Tariffs 1996 (USD per megawatt-hour)

	Wholesale	Retail
South/Southeast/Midwest	31*	74
North/Northeast	29	63

Notes: *When the Itaipu tariff is not included in this average, the value is $27 per megawatt-hour. Uses a 1996 foreign exchange rate of US$1 = R$1. To convert from USD per megawatt-hour to cents per kilowatt-hour, divide by 10. Thus, $74 per megawatt-hour equals 7.4 cents per kilowatt-hour.

Source: MME. 1998.

insufficient to cover the high fixed costs of Brazil's electric power sector.[24] (See Table 5.) Given these relatively high tariffs, utilities should have a stronger financial balance.

D. Efficient Electricity Use

Concerns over efficient electricity use began to appear in Brazil during the mid-1980s. Headed by the electric power sector, the objective was to reduce the need for fresh investments. However, efficiency gains have been held back by market barriers including the following:

- Decades of economic instability and soaring inflation
- Distorted industrial policy
- Lack of awareness of electricity conservation measures among end users
- Subsidized electricity prices
- Lack of capital or attractive financing for many consumers
- Lack of financial incentives for utilities to implement demand-side management programs.[25]

Many of these barriers have been lowered or even removed in recent years. Inflation has been largely controlled. Markets have opened up, with competition growing keener. Many consumers are now paying relatively high prices for electricity, and both the availability and awareness of efficiency measures are increasing. However, much more could be done to foster efficient energy use, given potential savings, soaring electricity demands, and increasing risks of electricity shortages nationwide.

Many distribution utilities in Brazil still have end-user efficiency programs that are merely symbolic. This is due to lack of experience, inability to recover program costs, and concern over shrinking sales revenues. While federal regulations allow utilities to recover demand-side management program costs in tariffs, utilities do not do so in practice. Furthermore, there are no mechanisms that allow utilities to recover net losses in revenues or receive a portion of the benefits to society generated by their demand-side management programs. A new regulation, however, requires recently privatized distribution companies to invest at least 1 percent of their total revenues on electricity efficiency, of which at least 25 percent is spent on end-uses rather than supply-side additions. This action may boost electricity conservation in the near future.

E. Environmental Impacts of Electricity Generation Technologies

All power generation technologies have environmental impacts, but the severity differs according to many variables, some of the most important of which are explained below.

Thermal Power. From 1990 through 1997, Brazil's thermal power plants largely used coal, oil, sugar cane bagasse,[26] leachate,[27] biomass wastes, and natural gas.[28] Approximately 80 percent of the carbon emissions from fossil fuel-fired power generation comes from steam coal, diesel oil, and residual fuel oil. (See Table 6.) Combustion of sugar cane wastes accounts for half of all the biomass-related carbon dioxide emissions.

Biomass sources are either fully or partially renewable, depending on harvesting method. Fully renewable sources include sugar cane bagasse, leachate, and plant wastes, which have zero net carbon dioxide emissions. Partially renewable biomass energy includes firewood, which absorbs carbon dioxide (fixation) as trees grow. In Brazil, this fixation offsets over 20 percent of the carbon dioxide released as firewood burns.[29] Burning sugar cane bagasse and other wood products to generate electricity is generally less efficient than burning a fossil fuel, but they generate less CO_2.

Table 6

Total CO_2 Emissions from Brazilian Thermal Power Generation

Fuel	**1993**		**1997**	
Fossil Fuels	**Gigagrams of Carbon**	**Percent**	**Gigagrams of Carbon**	**Percent**
Natural Gas	95	3	157	4
Coal	1,103	37	1,707	39
Diesel Oil	525	18	1,020	24
Fuel Oil	682	23	994	23
Other Sources	547	19	455	11
Total – Fossil Fuels	2,953	100	4,332	100
Biomass Sources				
Fuelwood	189	17	147	10
Sugar Cane bagasse	377	34	744	50
Leachate	279	25	394	26
Plant Wastes	265	24	207	14
Total – Biomass	1,109	100	1,492	100

Notes: One gigagram (Gg) is equivalent to one billion grams, or one thousand metric tons. The CO_2 emissions in this table do not account for carbon fixation occurring during the growth of renewable biomass. The net CO_2 emission of fully renewable biomass in Brazil is approximately zero. Rounding off may result in totals other than 100 percent.

Source: Schechtman, R., A.S. Szklo, and J. Sala. 1998.

Local air pollution emissions from existing thermal power plants have only minor impacts in some regions of the country. Damage is most severe in southern Brazil, where coal-fired plants use electrostatic precipitators to remove particulate emissions but do not have removal systems for SO_2 or NO_X. Emissions are also heavy in São Paulo state, where particulate matter emissions from sugar cane bagasse-fired plants can be severe depending on the properties of the bagasse used, the performance of the combustion system, and the control systems deployed.

Nuclear. Nuclear power currently plays a minor role in Brazil's energy system. Only the Angra I nuclear power plant — brought on-line in 1985 with a gross capacity of 657 megawatts — is currently in operation. Brazil plans two more nuclear power plants: Angra II (1,309 megawatts), scheduled to start up in 2000, followed by Angra III (1,309 megawatts), scheduled to start up in 2006.

Some analysts believe that nuclear could return to favor in Brazil since this form of power has virtually zero air pollution emissions,[30] and there is considerable concern over the greenhouse effect and regional impacts of pollution caused by conventional fossil fuel plants. However, electricity generation in Brazil is predominantly hydropower-based, and therefore greenhouse gas emissions are currently not appreciable. Moreover, natural gas is the main feature of the government's plans to expand power. Natural gas-fired plants feature low fixed costs, guaranteed rapid returns on investment, flexibility and modularity, rapid start-up, and relatively low levels of emissions. As in other countries, high capital costs, long-term disposal of nuclear waste, and public opposition also stand in the way of nuclear playing a larger role in the near future.

Hydropower. Much hydropower potential is still available at competitive prices in various parts of Brazil, but the full social and environmental costs of building these plants are not always considered.[31] The greatest of these costs lie in the resettlement of communities. Economic costs include compensation for land, relocation of towns and villages, construction of regional infrastructure, and compensation for impacts on affected ecosystems. These costs naturally rise the more densely populated the regions.

Recent experience indicates that social and environmental costs can be a significant portion of total costs of a hydropower project. This is particularly clear when lengthy negotiation is required to resettle communities. Social and economic costs are estimated on the basis of unit costs for each family affected, and rural versus urban areas. Also included are the costs of replacing community assets such as schools, recreation areas, and public buildings. To determine the unit cost per rural family, the Eletrobrás plan for 2015[32] used the social and environmental budgets for seven hydroelectric projects as a reference, where resettlement costs varied from $60,000 to $150,000 per family. For urban families, the unit cost ranged from $30,000 to $60,000. The average cost in rural areas is higher than that in urban areas because city residents often live in densely populated neighborhoods with low-cost housing while farmers are more spread out and have more valuable properties. When large sectors of the populace must be relocated, these costs can reach 30 percent of the total costs of a new hydropower project.

Concern over deforestation and the conservation of biological diversity affected by hydropower complexes is a relatively new issue in Brazil. The nation's environmental legislation requires that large-scale projects establish ecological stations "of a value proportional to the environmental damages to be offset" in order to equalize damages caused by the destruction of ecosystems. In tandem with environmental legislation, the Environmental Master Plan for the electric power sector recommends that hydropower projects should not be undertaken if "activities impose risks on the ecological functions of plant and wildlife [species], or result in the extinction of species."[33] Despite the electric power sector's acknowledgement of the importance of biodiversity, the impacts of hydropower projects on ecosystems involves complex issues that are difficult to balance in practice.[34]

During dam and reservoir construction, the submerged biomass decomposes, emitting greenhouse gases, particularly carbon dioxide, methane, and nitrous oxide. These emissions have been measured in hydropower projects in Brazil,[35] Canada[36] and Finland.[37] Numerous factors may affect atmospheric emissions from plant decomposition, including the size of the reservoir, the climate where the plant is built, and the quantity of submerged biomass.[38] Although still in the study phase at various research centers throughout the world, atmospheric emissions caused by hydropower generation should be studied further. This is especially true for Brazil because of its predominance in power generation. In this report, however, greenhouse gas emissions from hydropower plants were not considered due to the lack of reliable data.

Wind Power. Wind power is an intermittent, renewable source of electricity with low energy density. This alternative is potentially promising for certain parts of Brazil, particularly in the northeast because of the wind potential there, but cost may be a prohibitive factor. Environmental impacts include higher noise levels in wind-farm areas; electromagnetic interference, particularly of television reception; alterations to land use and the landscape; and, interference with birds and other winged wildlife. Further advances in technology and reductions in capital costs will be required before wind power can play a greater role in meeting Brazil's power needs.

III. Comparing Alternatives

A. Methodology

There are four steps in this analysis for comparing alternative sources of power generation:

- The analysis develops a framework that includes a baseline projection of power demand and a model to integrate supply and demand to evaluate costs.
- Capital, fuel, operations, and associated environmental costs for power generation technologies are converted to costs per kilowatt-hour.
- The model tests alternative policies for their impact on average generation costs and for changes in greenhouse gas and other emissions relative to the baseline projection of power demand.
- Model results indicate increased or reduced economic cost compared to the baseline, along with changes in power plant capacity, utilization, and emissions.

The authors developed a simple linear programming (LP) model to analyze the cost and environmental impacts of different power sector policies in Brazil.[39] (See Box 2.) This model allows analysts to capture detailed characteristics of the technologies used in the power sector, an important consideration over the relatively short time scale considered. Macroeconomic general equilibrium modeling might have been a preferred analytical method if the time scale were longer and Brazil's power sector were part of a more market-oriented economy. Market-based models do not accurately simulate heavily distorted markets. However, any model simulating Brazil's electricity sector is subject to uncertainty because consumer prices are partially subsidized and specific fuel costs are affected by cross-subsidies.

The LP model developed first calculates levelized, or lifecycle, costs[40] for each power generation option based on capital, fuel, operation and maintenance, and, if applicable, environmental costs. The model then determines the optimal combination of new plants needed to meet given levels of power demand, which is entered exogenously (from outside sources). Model constraints mimic policy measures and set limits over which values can be obtained. (See Appendix D.) The model does not attempt to forecast power plant construction schedules or even the necessary power capacity. Rather, it compares the impact of different policy options on technology choices and environmental quality.

All modeling has limitations. Optimization models like the one used in this analysis have a finite ability to mirror the reality of consumer behavior or the ripple effect of alternative policies throughout the

Box 2

A Guide to Linear Programming for Power Sector Analysis

Analysts use linear programming (LP) models to optimize combinations of inputs whose values are valid only over specific ranges. For example, power planners and electric utilities use LP models to determine the types of power plants required to meet least-cost power demand over time while meeting limitations in pollution emissions, energy sources, and manufacturing capacity. Models can help planners analyze alternatives, but non-quantitative factors must also be considered in designing real-life systems.

Researchers use two classes of models to analyze energy systems, LP models are often called “bottom-up” models because they contain detailed information about technology and costs. They have rich engineering detail and rely on user input to simulate broader economic conditions. Top-down models, on the other hand, begin from a higher level of economic reality by simulating the interaction of supply and demand in the main sectors of an economy. While top-down models have less detailed information about energy technologies and costs, they capture the reality of consumer behavior better than bottom-up models. Some models, like MARKAL-MACRO, try to integrate the economic reality of top-down models with the engineering detail of bottom-up models.

Researchers at Battelle created a generic LP model which each of the country teams in this study modified to analyze least-cost power options according to the conditions in their specific countries. The model can choose among 17 different types of power plants (coal, petroleum, natural gas, nuclear, hydroelectric, or renewable) to meet power demand. The model divides the country into as many as five regions to capture variations in energy availability, fuel cost, and environmental limitations. Simulation begins with a base year (1995) and then determines the amount of new capacity from each type of power plant needed to meet demand over five-year intervals.

After analysts enter technology and cost characteristics of the power plant options, the model calculates the levelized, or lifecycle costs of power generation. Levelized cost analysis accounts for all the costs of building, fueling, operating, and controlling pollution from power systems and spreads them out over the economic life of the plant. In this way, the costs of delivering power to users from nuclear plants (with high construction and low fuel costs) can be compared directly with the costs of providing power from combined-cycle plants (low construction costs and high fuel costs). Analysts also enter power demand over time and regions. These values are calculated separately according to estimates of economic growth and power demand intensity.

The actual linear program will then find the minimum cost combination of power plants needed to meet the demand. Additional constraints can include emission caps on pollutants such as sulfur dioxide, manufacturing limitations for power generation equipment such as nuclear reactors, energy supply limitations such as hydropower capacity, and transmission line characteristics that limit the amount of power that one region can send to another. For a given time period, the LP will choose the cheapest power source available and continue to use that technology until a constraint prevents its use. LP models need expert input to define when constraints are needed to simulate reality.

economy. Although they provide realistic technical and performance characteristics, they tend to overestimate the impact of the single cheapest alternative. Finally, optimization models neither fully account for investor preference, such as risk mitigation or financial guarantees, nor ensure that energy security and diversity issues are addressed without input from the modeler. Still, the model can be a useful tool to weigh policy alternatives.

Power generation options in the model include wind power, bagasse, pulverized coal, fluidized bed coal, diesel generators, residual fuel oil, gas-fired combined-cycle, hydropower, nuclear, and energy conservation.[41] The costs and operational efficiencies of the technologies vary as indicated in Table 7. Brazil is expected to make greater use of combined heat and power (CHP), also known as cogeneration, for which the modelers created a separate module (described below). Other power generation technologies are also modeled but do not compete economically with the alternatives. Three of these alternatives are natural gas fuel cells, biomass gasification, and solar thermal power plants.

Table 7

Costs and Technical Characteristics for Selected Power Options in 2000

Technology	Capital Costs ($ per kilowatt)	O&M Costs ($ per kilowatt-hour)	Efficiency (%)
Pulverized Coal	1,040	0.009	37
Fluidized Bed Combustion	1,250	0.010	39
Gas-fired Combined-cycle	495	0.007	50
Bagasse (Rankine Cycle)	1,100	0.010	25
Bagasse (Gasification)	2,400	0.012	35
Diesel Oil	1,000	0.008	30
Residual Oil	1,070	0.011	30
Nuclear	1,600	0.009	33
Wind	1,100	0.010	–
Large Hydropower	815-1,540	0.0013-0.004	–

Note: See Appendix B for complete list and sources.

B. Assumptions and Scenarios

Forecasting the level of power demand through 2015 was the first step in considering alternative growth scenarios. Three power demand forecasts are presented below based on different assumed levels of economic growth. (See Table 8.) The effects of the recent global financial crisis are largely included in these forecasts. These growth scenarios mirror those used in the Eletrobrás expansion plan through 2007, although economic growth assumptions were extended through 2015.[42] The reference scenario is used as the baseline for most of the results that follow.

Power demand is forecast based on these economic growth rates and the elasticity of power demand.[43] These demand forecasts assume that Brazil will make considerable progress in lowering the elasticity of power demand by 2015. The elasticity in Brazil's well-developed economic regions, for example, will converge rapidly to levels found in the industrialized world by 2015. Elasticities in less-developed regions will also fall rapidly, but remain well above those levels.

Table 8

GDP Growth Rates Used in the Power Demand Forecast (Percent)

	1995-2000	2000-2005	2005-2010	2010-2015
High-Growth Scenario	1.5	4.7	4.9	5.6
Reference Scenario	0.8	2.8	4.9	4.9
Low-Growth Scenario	0.7	1.7	4.6	4.6

Sources: Eletrobrás. 1998. *Plano Decenal de Expansão* – 1998-2007; Schaeffer, R., A. Szklo, and J. Marques. 1999.

Power forecasts based on these assumptions indicate that electricity demand will grow in the reference case by an average rate of 3.6 percent between 1995 and 2015, reaching nearly 600 terawatt-hours by 2015. (See Table 9.) The difference between the high- and low-growth scenarios is about 25 percent, indicating that small differences in assumptions are magnified over the 20-year study period.

Table 9

Electric Power Demand Forecast, 1995-2015 (terawatt-hours)

	1995	2000	2005	2010	2015	Average Annual Growth Rate 1995-2015 (Percent)
High-Growth Scenario	291	329	433	539	694	4.4
Reference Scenario	291	325	405	505	592	3.6
Low-Growth Scenario	291	322	368	453	524	3.0

Sources: Eletrobrás. 1998. *Plano Decenal de Expansão* – 1998-2007; Schaeffer, R., A. Szklo, and J. Marques. 1999.

Several additional assumptions were made to construct the baseline and alternative scenarios and are described below:

- A single discount rate of 15 percent was assumed for all scenarios, consistent with a privatized power sector.

- Brazil's power sector relies on long-term planning since hydropower plants have long construction periods. Plants already in the planning stage or under construction are not included in the least-cost calculations, although their costs and future generation count in the results that follow.[44] The two nuclear plants under construction are also omitted from the least-cost analysis.

- Diesel power generation depends on subsidies offered by the Fuel Compensation Account administered by Eletrobrás. These subsidies continue in the baseline scenario, but are discontinued in all other scenarios after 2005 as a likely policy option.

- Regional cooperation with neighboring countries will allow Brazil to rely on relatively inexpensive natural gas and power imports. Bolivia and Argentina will likely be the source of much of Brazil's imported gas. Power imports from Venezuela and Argentina are simulated in the least-cost analysis. Transmission capacity grows steadily to over 2.7 gigawatts via Argentina and 200 megawatts via Venezuela. Transmission capacity between the southern and northern grids also expands to 2.5 gigawatts.

- Natural gas availability increases rapidly as new pipelines are completed from Bolivia and Argentina, and as reforms encourage greater domestic production. By 2010, nearly 17 billion cubic meters of natural gas will be available for power generation, enough to fuel approximately 12 gigawatts of power generation.

- Only the cost of building transmission infrastructure over long distances is included in the total. Other infrastructure costs for transmission and distribution would be required, but since they are nearly identical for all centralized power plants, they are ignored in the analysis. This assumption may put decentralized power systems such as fuel cells, photovoltaics, and small wind turbines at a disadvantage, but most of these technologies would not be competitive by 2015 in any event.

Table 10

Estimated **Energy Source Prices**

	2000	**2015**
Brazilian Coal (US$/t) (1)	23	23
Imported Coal (US$/t) (2)	48	48
Natural Gas (US$/GJ) (3)	2.5	2.5
Liquefied Natural Gas (US$/GJ)	4.3	4.3
Uranium (US$/MWh)	8.2	8.2
Diesel Oil (US$/t) – medium price (4)	442	649
Diesel Oil (US$/t) – high price (5)	442	859
Residual Fuel Oil(US$/t) – medium price (4)	149	164
Residual Fuel Oil (US$/t) – high price (5)	149	217
Ethanol – S/SE/MW (US$/m3)	280	280
Ethanol – N/NE (US$/m3)	560	560
Bagasse (US$/t) (6)	7[46]	7

Notes: (1) Based on prices for coal from Candiota and Santa Catarina mines. (2) Price of Colombian coal. (3) Take-or-pay contract for Bolivia-Brazil pipeline.[47] (4) Based on oil prices of $22/barrel in 2015 (1997 prices); (5) Based on oil prices of $29/barrel in 2015 (1997 prices)[48]; (6) Price used only in the Carbon Elimination Scenario.

Sources: "International Energy Outlook 1999"; Schaeffer, R., A. Szklo, and J. Marques. 1999.

- Energy prices are expected to change, as indicated in Table 10.[45] For petroleum products, the baseline and advanced technology scenarios used the medium price. The local environmental and carbon elimination scenarios used the high price.

The baseline scenario serves as a yardstick for measuring the impact of alternative policies. The alternative scenarios test the impact of these policies on Brazil's power sector. (See Table 11.)

Table 11

Policy Scenarios Considered in the Study

Scenario	Key Policy Levers
Baseline	Continued reform and privatization, expanded use of cogeneration, falling electricity intensity.
Advanced Technology	Same as baseline plus reduction in technology costs, use of lower-level environmental fees, extended economic life for clean options.
Local Environmental Control	Same as baseline plus use of upper-level environmental fees, increased availability of clean fuels, extended economic life for clean options, and cost reduction in environmentally clean technologies.
Carbon Elimination	Same as baseline plus zero carbon emissions tolerance, increased availability of clean fuels, decreased availability of hydropower.

The advanced technology and local environmental control scenarios incorporate "shadow costs" for the estimated environmental damage due to sulfur dioxide, nitrogen oxide, particulates, and carbon dioxide. Analysts can use shadow environmental costs to plan a least-cost energy system or they might be used by decision-makers to set regulations; the plants built based on this analysis, however, would not incorporate these environmental costs into the price of the power they sell.

Power plant emissions harm human health, agriculture, and infrastructure and degrade the quality of life in other ways (loss of clear skies, etc.). Researchers use detailed field studies and laboratory analysis to estimate the environmental costs of power plant emissions. Quantifying their damage is difficult and controversial. Many policy-makers choose to ignore environmental costs, even in power sector planning exercises, but no cost is clearly incorrect. This study estimates environmental costs using other country studies.[49] (See Table 12.)

Table 12

Environmental Costs of Selected Pollutants (US dollars per ton of pollutant)

	Lower Limit	Upper Limit
Sulfur Dioxide (SO_X)	1,280	3,770
Nitrogen Oxide (NO_X)	470	2,010
Particulates (RO_X)	1,130	1,450
Carbon Dioxide (CO_2)	7	120

Source: *ExternE – Externalities of Energy Use: A Research Project of the European Commission.* See this reference for a full description of assumptions and findings.

These estimates are relatively high compared to those used in other developing nations[50] because many Brazilians place a high value on the environment.

Cogeneration is included as a type of power supply but it differs from the technologies listed above because it also provides a portion of steam energy with considerable economic value. The model includes a separate module for cogeneration that assesses how much of the market's needs cogenerated power could meet. The module assumes a fixed proportion of steam and power output; it also assumes that the independent producer is remunerated at the marginal expansion cost that the system avoids. In other words, cogeneration is modeled as another type of power supply and must compete on a least-cost basis with the other supply options. A cap, or maximum amount of cogeneration that can be chosen, is also used. This cap just exceeds 10 gigawatts by 2015, about 10 percent of the total system capacity then. This figure is based on the likely market for steam energy. Levelized costs range from $26.5 per megawatt-hour for cogeneration using black liquor (an industrial waste) to $44 per megawatt-hour for cogeneration using gas turbines.

The model also introduces energy conservation as an alternative type of energy supply. Energy conservation and efficiency projects can offset the need for additional supply, often at considerably lower cost. In the model, levelized costs for efficiency and conservation range from $3 per megawatt-hour for activities in the industrial sector to $5 per megawatt-hour in other sectors. In some case studies, efficiency improvements actually had negative costs, but this modeling assumes the need to spend money to overcome non-market barriers in implementing savings.[51] As in the cogeneration module, there is a maximum level of conservation or efficiency that can be implemented in a given time period that in most scenarios amounts to 4 gigawatts by 2015.

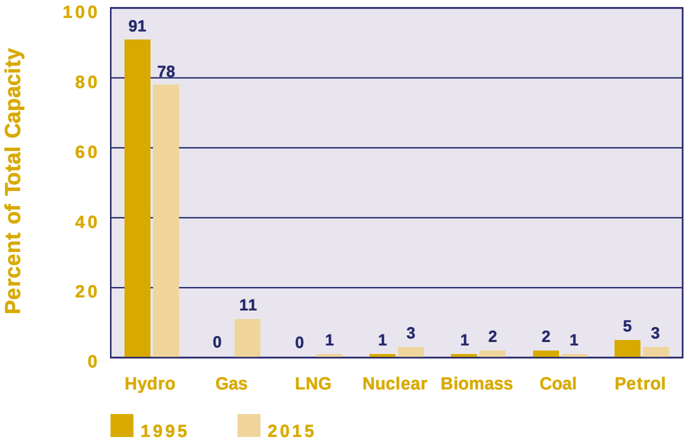
C. Results

Baseline Scenario. In the baseline scenario, current government policies in Brazil concerning privatization of the power sector continue. Contrary to today's situation, the new combined-cycle power plants would operate in baseload configuration rather than as peaking units. This results in lower prices for power. Existing diesel and residual fuel oil plants continue to receive subsidies in remote locations. No restrictions on carbon dioxide emissions or external environmental factors are imposed. The model assumes a pay-back period of 10 years, meaning that investments channeled to generation technologies must be paid off rapidly.

The installed capacity in 2015 reaches 94 gigawatts, 68 percent higher than in 1995. (See Tables 13 and 14.) New additions to this scenario between 1995 and 2015 account for 38 gigawatts, of which 25 gigawatts were planned before 1995. Least-cost analysis determines the remaining 13 gigawatts. Natural gas plants increase from about zero percent of installed capacity in 1995 to 11 percent in 2015. (See Figure 3.) Nuclear also rises to meet 3 percent of capacity needs, but these additions come from plants already planned and were not part of the least-cost solution. Biomass and LNG capacity increase slightly, while coal and petroleum decline. Energy efficiency and conservation play important roles in limiting an even greater reliance on fossil fuel power generation, avoiding 4 gigawatts of capacity expansion in 2015. Approximately 2 gigawatts of installed capacity in Venezuela and Argentina generate electricity to transmit to Brazil in the least-cost solution. Cogeneration units, installed mainly in refineries and steel mills, account for 8.5 percent of demand in 2015.

Figure 3

Installed Capacity in the **Baseline Scenario**



Note: Rounding off may result in totals other than 100 percent.

Total costs reach $183 billion and include the capital, fuel, and maintenance costs of: 1) plants planned before 1995; 2) cogeneration units installed between 1995 and 2015; and 3) the remaining plants needed to satisfy the least-cost power demand. The total does not include intra-regional transmission and distribution costs.

In the high economic growth case, installed capacity in 2015 climbs to 110 gigawatts. The same capacity share of natural gas and biomass plants is required in 2015, but an additional 4 gigawatts of LNG-fired combined-cycle plants are needed in the north and northeast. For the low-growth case, capacity share for natural gas plants declines to 5 percent of the nation's total. Even for the low-growth case, the cogeneration required is 10 percent of the total demand because cogeneration is the most economical.

The amount of power generated from the capacities calculated above depends on the capacity factors defined for each technology. The share of power generation in 2015 provided by combined-cycle power plants fueled with natural gas is greater than the share of installed capacity. This is due to the high capacity factors assumed for combined-cycle units, reflecting the interest of private investors in rapid pay-back on their investments. (See Appendix B.)

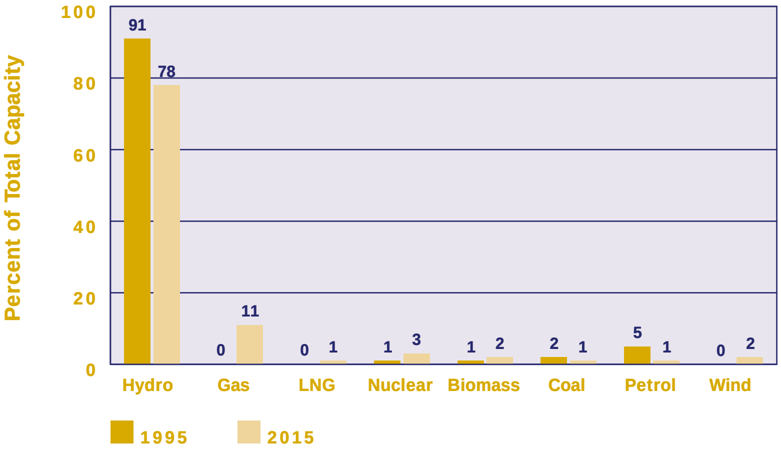
Carbon dioxide emissions increase by an astonishing 325 percent during the period under analysis (compared to a 105 percent growth in power generation) due largely to the rapid growth in natural gas-fired combined-cycle units. (See Table 14.) However, the intensity of carbon dioxide emissions from power generation remains low even in 2015 because hydropower still plays a leading role and other generation technologies are all relatively clean. Although emissions of sulfur dioxide and particulates more than double during the period, the intensity of emissions remains stable. Nitrogen oxide emissions increase nearly five-fold, mainly due to the greater use of natural gas in power generation turbines.

Advanced Technology Scenario. In the advanced technology scenario, the costs of alternative power generation technologies drop over time compared to the baseline through accelerated policies in research and development, demonstration, and deployment. (See Appendix B.) Also, the efficiency of some conventional technologies, such as atmospheric fluidized bed combustion, is assumed to rise. The model uses the lower value of environmental costs. (See Table 12.) The model also uses a pay-back period of 10 years for conventional technologies and a pay-back period of 30 years for alternative technologies, meaning that the new technologies will receive greater incentives. The extra cost of the policy subsidies required to achieve the longer pay-back is included in the final cost value presented. Existing diesel and residual fuel oil plants receiving subsidies to operate in remote, off-grid locations are discontinued after 2005.

Installed capacity in 2015 reaches nearly 94 gigawatts, about the same as the baseline scenario. (See Tables 13 and 14.) In this scenario, 13 gigawatts of new capacity are added from the least-cost analysis while another 25 gigawatts are added outside the cost minimization (plants planned before 1995). The only noticeable change from the baseline scenario is that wind power capacity increases slightly due to the effect of environmental costs on other options. (See Figure 4.) Natural gas represents 11 percent of the installed capacity in 2015.

Figure 4

Installed Capacity in the Advanced Technologies Scenario



Note: Rounding off may result in totals other than 100 percent.

Cogeneration accounts for 65 terawatt-hours of generation in this scenario. The avoided long-term marginal cost of capacity expansion is larger in this scenario than in the baseline, meaning that more cogeneration plants will be used. This reduces the market that electric power utilities need to supply. Efficiency and conservation play a similar role in both the advanced technology and baseline scenarios by displacing the need for 4 gigawatts of supply capacity. Power imports from Venezuela and Argentina are also used as in the baseline case.

The total cost of the advanced technology scenario is $181 billion. This cost includes the subsidies given to alternative technologies to allow amortization in 30 years instead of 10. Total cost declines because the model assumes that improved technologies will have lower capital costs and because other operational costs fall slightly. The actual cost of power does not include estimated environmental damages.

Installed capacity in the high-growth case is again 110 gigawatts in 2015 while the low-growth case would require 91 gigawatts. Wind power generation costs are higher than both hydroelectric and natural gas, meaning that wind plays a smaller role under assumptions of low growth, reaching only 0.3 percent of total capacity.

Carbon dioxide emissions rise less than 300 percent during the period under analysis, slightly less than in the baseline scenario. (See Table 14.) In other words, the lower values of externalities plus technological advances did not yield a significant reduction in carbon emissions. The pre-existing diesel-powered generators operating in remote locations are discontinued after 2005, accounting for most of the reduction. For other pollutants, there is a near tripling of emissions of nitrogen oxides due to greater natural gas consumption. Sulfur dioxide emissions decrease by 56 percent to 135,000 tons due to closing of diesel plants.

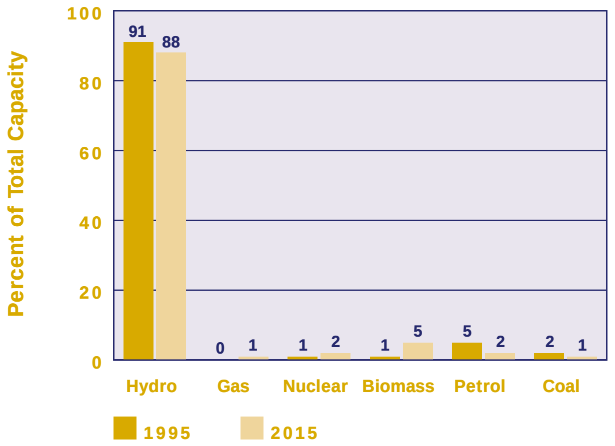
Local Environment Control Scenario. In the local environmental control scenario, environmental restrictions largely determine the technologies employed. The model uses the higher level of environmental damage. (See Table 12.) Subsidies are given to the cleanest technologies (solar, hydro, wind, fuel cell, biomass gasification), to allow amortization in 30 years instead of 10 as in the advanced technology scenario, but the same subsidy is also applied to small hydropower plants. The existing diesel and residual fuel oil plants receiving subsidies to operate in remote locations are discontinued after 2005. Availability of bagasse from sugar cane also expands by 50 percent in 2015 due to specific policies to widen availability. The increased availability of bagasse would require coordinated policies between the transport and power sectors since bagasse can also be used to fuel vehicles.

The installed capacity in 2015 reaches 100 gigawatts, about 3 percent higher than the baseline scenario. (See Tables 13 and 14.) The installed capacity in this scenario is considerably higher than the baseline because many of the new plants have relatively low capacity factors so more of them are needed to provide the same output. Electricity conservation and imports play the same role as in the previous scenarios.

Figure 5

Installed Capacity in the

Local Environment Control Scenario



No plants using LNG are constructed during this scenario.

Note: Rounding off may result in totals other than 100 percent.

Power generation continues to be based predominantly on hydropower, with capacity increasing from 78 percent of the baseline's total in 2015 to 88 percent in the local environmental control scenario. (See Figure 5.) Biomass capacity increases from 2 percent in the 2015 baseline to 5 percent in the local environmental control scenario. Natural gas use declines from 11 percent to almost nothing, while LNG and wind are no longer part of the least-cost solution. Wind power is not part of the least-cost solution because hydropower is included in the set of subsidized clean options in this scenario, giving it a lower levelized cost than wind. Cogeneration output reaches 60 terawatt-hours in this scenario by 2015, slightly less than the baseline and technology scenarios. Efficiency and conservation play a similar role as in previous scenarios by displacing the need for 4 gigawatts of supply capacity. Two percent of Brazil's capacity would continue to be provided by imports from Venezuela and Argentina.

The total full cost is $179 billion, again slightly less than in the baseline. The costs of the plants determined by the least-cost analysis are higher, however. (See Table 14.) The actual cost of power does not include estimated damages to the environment.

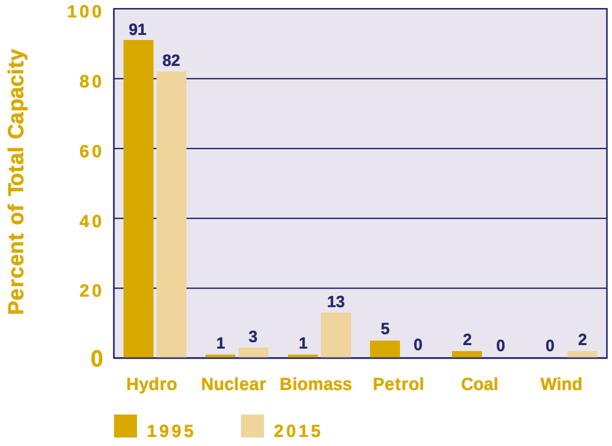
Carbon dioxide emissions decline by 82 percent compared to the baseline during the period under analysis. The decline reflects the appreciable percentage of power generation based on hydroelectric and renewable sources. Sulfur dioxide emissions also decline by nearly 75 percent compared to the baseline, but particulate emissions increase by 12 percent due to greater use of conventional bagasse for power generation.

Carbon Elimination Scenario. The carbon elimination scenario assumes that Brazil will install only electric power generation technologies that have no net carbon dioxide emissions and only minor impacts on watersheds or landscapes. Plants planned or under construction that do not meet this requirement would be shelved or retired. Hydropower and nuclear plants have limited availability,[52] while coal and natural gas-based plants are avoided. A new technology — the alcohol-based fuel cell — is modeled with a pay-back period of 30 years. Availability of bagasse in 2015 expands nearly four-fold compared to the baseline case. Again, boosting availability of bagasse so dramatically would require close coordination with the transport sector. Bagasse costs would likely increase given higher demand, but greater economies of scale are also likely to emerge in bagasse production facilities, helping to keep costs down.

Installed capacity in 2015 reaches 97 gigawatts. (See Tables 13 and 14.) Power generation in 2015 is 98 percent renewable under this scenario. The outstanding 2 percent comes from the nuclear power plants that were already part of the power mix. (See Figure 6.) More of the capacity additions are added under least-cost analysis in this scenario (27 gigawatts) than from the plants already in the planning stage (14 gigawatts) because of limitations on carbon emissions. Conservation and imports continue to help displace the need for greater domestic generation supplies. Hydropower continues to hold the largest share of capacity. However, new technologies such as wind-power and biomass, replace hydropower as its potential is depleted.

Figure 6

Installed Capacity in the **Carbon Elimination Scenario**



Note: Rounding off may result in totals other than 100 percent.

Total costs climb to $208 billion. This includes the costs of plants already under construction and subsidies given to renewable technologies to allow amortization in 30 years instead of 10.

Table 13

Installed Capacity by Scenario and Source (gigawatts)

	1995	Baseline 2015	Advanced Tech 2015	Local Env 2015	No-carbon 2015
Coal	1.1	1.4	1.4	1.4	0.0
Biomass	0.8	1.9	1.9	5.3	13.0
Petroleum	2.6	3.2	1.7	1.7	0.0
NG & LNG	0.0	11.8	11.6	0.8	0.0
Hydropower	50.7	73.3	73.1	87.8	80.0
Nuclear	0.7	2.6	2.6	2.6	2.6
Wind	0.0	0.0	1.6	0.0	1.5
Total	55.9	94.2	93.9	99.6	97.1

Note: This table does not include self-production, cogeneration or energy imported from Argentina and Venezuela.

Cogeneration supplies only 48 terawatt-hours of generation in this scenario because units are limited to those with no net carbon emissions. These applications include black liquor, other renewable biomass sources, and reuse of residual gases from the industrial sector that would be emitted in any event.

Under high-growth conditions, 122.5 gigawatts of capacity would be required by 2015, with sugar cane bagasse plants climbing to 16 percent of installed capacity. In low-growth conditions, biomass capacity would decline from 13 percent to 8 percent, while hydropower would rise to 87 percent.

Carbon dioxide emissions cease during the period under analysis because this scenario assigns top priority to technologies that support environmental sustainability. Sulfur dioxide emissions also decline by 50 percent compared to the baseline, but remain significantly higher than the technology and environmental scenarios, due to heavy reliance on biomass. Particulate emissions increase by 150 percent for the same reasons.

Table 14

Final Results for the Four Different Scenarios Considered

	Units	1995	Baseline 2015	Advanced Tech 2015	Local Env 2015	No-Carbon 2015
Capacity						
Generation(1)	TWh	264	541	532	535	544
Capacity(2)	GW	56	94	94	100	97
Costs						
Cumulative Discounted Cost(3)	US$ Billion	–	183	181	179	208
Cogeneration	US$ Billion	–	24	17	21	15
Planned Before 1995	US$ Billion	–	134	130	130	120
Least-Cost (embodied subsidies(4))	US$ Billion	–	25 (0)	34 (0.2)	28 (5)	73 (13)
Emissions						
SO_2	Thousand tons	166	306	135	81	154
NO_X	Thousand tons	23	110	89	28	35
RO_X (Particulates)	Thousand tons	12	26	19	29	65
CO_2	Million tons C	3.4	14.5	13.3	2.6	0.0
Emission Intensities						
SO_2	Grams per kWh	0.63	0.60	0.27	0.16	0.30
NO_X	Grams per kWh	0.09	0.22	0.18	0.06	0.07
RO_X	Grams per kWh	0.05	0.05	0.04	0.06	0.13
CO_2	Kilograms per kWh	0.013	0.29	0.27	0.005	0.000

Notes: (1) Generation excludes self-production and electricity imported from Venezuela and Argentina. (2) Capacity includes plants installed between 1995 and 2015 but does not include electricity savings by efficiency and conservation measures and the installed capacity in Argentina and Venezuela that provides electricity to Brazil. (3) Cumulative Discounted Cost is the sum of three parts: cumulative costs of cogeneration plants installed between 1995 and 2015, cumulative costs of plants planned before 1995 but installed between 1995 and 2015, and cumulative costs of capacity expansion planned in the least-cost analysis between 1995 and 2015. (4) Subsidies are given in the advanced technology, local environment, and no-carbon scenarios to allow some technologies to be amortized in 30 years instead of 10.

IV. Conclusions

Regardless of the current economic instability, power demand in Brazil will continue to grow appreciably over the next two decades. Institutional and regulatory reforms under way in the power sector could affect how the country meets the rising demand for electricity.

Hydropower plants will continue to play the most important role, despite increasing costs and controversy due to the large number of power plants under construction or in the advanced planning stage. Although hydropower plants have almost no local or global air pollution, other environmental and social disadvantages may slow their use.

Reforms currently being implemented will rely on greater participation of the private sector. These investors are likely to minimize risk by avoiding hydropower plants that have long construction periods and significant chance of cost overrun. The private sector will likely rely mainly on combined-cycle plants fueled by natural gas that have low capital costs, short construction times, modularity, and high efficiency. Brazil's power system is oversized because it was designed to handle the entire load curve throughout the year. Since Brazil relies on hydropower more than most countries, the imbalance is significant. Combined-cycle plants can also help address this problem of overcapacity.

Greenhouse gas emissions will remain relatively low under the expansion plans that Brazil's power sector is most likely to pursue. Although carbon dioxide emissions more than quadruple by 2015 in the baseline scenario, they continue to be extremely low in absolute terms. In the advanced technology scenario, wind power could replace diesel generation in remote locations, cutting sulfur and carbon emissions in the process.

In the local environmental control and carbon elimination scenarios, the projected increases in electricity generation based on bagasse would be linked to ethyl alcohol production for automotive use since both fuels rely on sugar cane wastes. Bagasse could become the most widely used power generation option after hydropower if Brazil were to consider the full environmental costs of power production or restrict technology options to those with almost no carbon dioxide emissions. If the price of bagasse remained relatively low, Brazil could service the electricity market sustainably for less than the total cost of the baseline scenario or, at most, 14 percent more.

In all four scenarios, demand-side electricity conservation plays a cost-effective role in displacing new capacity additions while reducing local pollution and greenhouse gas emissions. There remains enormous potential for cost-effective electricity efficiency improvements; consequently, there is great promise for reducing the environmental burden of electricity production and transmission without compromising the quality of the services end users demand.

Regional cooperation with other South American nations (Argentina, Venezuela, and Bolivia, for example) could also play a vital role in Brazil's energy future. Natural gas imports from Argentina and Bolivia will be essential in a reformed and privatized power sector. Power imports from Argentina and Venezuela can also be cost effective during certain periods of the year when Brazil's hydroelectric dams lack water for power generation.

Brazil appears set to play a unique role within the context of the UN Framework Convention on Climate Change. It is providing constructive options to motivate the international community to agree on reducing greenhouse gas emissions equitably. Just as importantly, it could set an important example for other developing countries by achieving economic growth that does not sacrifice local or global environmental quality.

Appendix A: Bibliography

Abud, A. 1999. Desvio Informal — Uma Análise das Perdas Comerciais de Energia Elétrica no Setor Informal da Economia e em Comunidades Faveladas no Brasil. Rio de Janeiro: COPPE/UFRJ. MSc. Thesis.

Bernstein, M., S. Hassell, P. Bromley, R. Lempert, J. Muñoz, and D. Robalino. 1999. "Developing Countries and Global Climate Change: Electric Power Options for Growth." Pew Center on Global Climate Change, Arlington, VA. June.

Bertsimas, D., and J. Tsitsiklis. 1997 *Introduction to Linear Optimization*. Athens: Athena Scientific.

Carpentieri, E., and W. Larson. 1993. "Future Bagasse-Based Power Generation in Northeast Brazil." *Bagasse and Bioenergy* 4 (3): 149-173.

Carvalho, A. 1995."High Capacity Factor Wind Energy Systems." *Journal of Solar Engineering* 117: 137-143.

De Laquil, P., M. Kearney, R. Diver, and M. Geyer. 1993. "Solar-Thermal Electric Technology." In *Renewable Energy Sources for Fuels and Electricit*y. Washington DC: Island Press: 213-296.

EIA. 1995. "Electricity Generation and Environmental Externalities: Case Studies." Washington, DC: US Department of Energy, Energy Information Administration.

EIA. 1997. "Cost and Performance of Clean Coal Technology in Brazil: Draft Final Report." Washington, DC: U.S. Department of Energy, Energy Information Administration.

EIA. 1999. "Country Analysis Brief: Brazil." Washington, DC: U.S. Department of Energy, Energy Information Administration. July.

EIA. 1999. "International Energy Outlook 1999." Washington, DC: US Department of Energy, Energy Information Administration. See also http://www.eia.doe.gov/oiaf/ieo99/home.html.

Eletrobrás. 1990. *Plano Diretor do Meio Ambiente*. Rio de Janeiro: Eletrobrás.

Eletrobrás. 1993. *Plano 2015* : *Projeto 7: A Questão Ambiental e o Setor Elétrico*. Rio de Janeiro: Eletrobrás.

Eletrobrás. 1998. *Plano Decenal de Expansão — 1998-2007*. Rio de Janeiro: Eletrobrás.

ExternE-Externalities of Energy Use: A Research Project of the European Commission. Available at http://externe.jrc.es.nletter6.html.

Feitoza, S., E. Serra, and M. Nascimento. 1999. "Células combustíveis, etanol e co-geração: ideal para o Brasil?" *Eletricidade Moderna*: 124-131, January.

Gagnon, L., and J.F. van de Vate. 1997. "Greenhouse Gas Emissions from Hydropower — The State of Research in 1996." *Energy Policy* 25 (1): 7-13.

Geller, H., G.M. Jannuzzi, R. Schaeffer, and M.T. Tolmasquim. 1998. "The Efficient Use of Electricity in Brazil: Progress and Opportunities." *Energy Policy* 26 (11): 859-872.

Goswami, D. 1998. “Solar Thermal Technology: Present Status and Ideas for the Future.” *Energy Sources* 20: 137-145.

Hamilton, K., and A. Giles. 1996. “Air Pollution and Green Accounts.” *Energy Policy* 24 (7).

Ministério das Minas e Energia — MME — Brasil. 1998. Balanço Energético Nacional. Brasília: MME.

Pimenta, J. 1999. “Células de combustível: energia limpa para o desenvolvimento sustentável.” *Eletricidade Moderna*: 224-235, April.

Rosa, L. P., M.T. Tolmasquim, and J.C. Pires. 1998. *A reforma do setor elétrico no Brasil e no mundo: uma visão crítica*. Rio de Janeiro: Relume Dumará: COPPE, UFRJ.

Rosa, L.P., R. Schaeffer, and M.A. dos Santos. 1996. “Emissões de Metano e Dióxido de Carbono de Hidrelétricas Comparadas às de Termelétricas Equivalentes.” *Cadernos de Energia* 9 (1): 111-155.

Rosa, L. P. and R. Schaeffer. 1995. Global Warming Potentials: The Case of Emissions from Dams. *Energy Policy* 23 (2): 149-158.

Rosa, L.P., and R. Schechtman. 1996. “Avaliação de Custos Ambientais da Geração Termelétrica: inserção de variáveis ambientais no planejamento da expansão do setor elétrico.” *Cadernos de Energia* 9 (2): 168-214.

Rudd, J.W.M., R. Harris, C.A. Kelly, and R.E. Hecky. 1993. “Are Hydroelectric Reservoirs Significant Sources of Greenhouse Gases?” *Ambio* 22(4): 246-248.

Schaeffer, R., M. Tolmasquim, A. Szklo, and M. Tavares. 1999. *Impactos da Liberação da Importação de Derivados sobre a Indústria de Refino Nacional*. Rio de Janeiro: ANP/COPPE/UFRJ.

Schechtman, R., A. Szklo, and J. Sala. 1998. *Determinação das Emissões de Carbono Derivadas do Sistema Energético Brasileiro — abordagem bottom up, Programa de Planejamento Energético/ COPPE/UFRJ — Projeto BRA/95/G31 — Enabling Brazil to Fulfill its Commitments to the UN Framework Convention on Climate Change*.

Slovic, P. 1987. “Perceptions of Risk.” *Science* 236: 280-285.

Tudera, M., S. Guerra, and R. de Almeida. 1997. “Alocação da Renda Gasífera: Uma Análise do Gasoduto Brasil-Bolívia.” *Revista Brasileira de Energia* 6(2).

Zylbersztajn, D., and S. Coelho. 1993. Colheita Mecânica de Cana e Economicidade da Cogeração. *Anais do VI Congresso Brasileiro de Energia*. Rio de Janeiro.

Appendix B: Technology and Economic Characteristics

		2000	2005	2010	2015
Fuel Cell	Capital Cost ($/kW)	1,400 (a, b, c)	1,250 (a, b, c)	1,200 (a)	1,000 (a)
				1,100 (b, c)	900 (b, c)
	Capacity Factor (%)	85 (a, b, c)	85 (a)	85 (a)	85 (a)
			90 (b, c)	92 (b, c)	95 (b, c)
	O&M ($/MWh)	6.5 (a, b, c)	5.5 (a, b, c)	5.5 (a)	5.0 (a)
				4.5 (b, c)	4.0 (b, c)
	Efficiency (%)	45 (a, b, c)	45 (a)	50 (a)	53 (a)
			53 (b, c)	55 (b, c)	60 (b, c)
Thermo-Solar Generation (SEGS)	Capital Cost ($/kW)	3,500 (a, b, c)	3,500 (a, b, c)	3,000 (a, b, c)	3,000 (a)
					2,500 (b, c)
	Capacity Factor (%)	25 (a, b, c)	25 (a, b, c)	25 (a, b, c)	25 (a, b, c)
	O&M ($/MWh)	15 (a, b, c)	13 (a, b, c)	10 (a, b, c)	10 (a, b, c)
Wind Generation	Capital Cost ($/kW)	1,100 (a, b, c)	1,000 (a, b, c)	900 (a, b, c)	800 (a, b, c)
	Capacity Factor (%)	25 (a, b, c)	30 (a, b, c)	35 (a, b, c)	35 (a, b, c)
	O&M ($/MWh)	10 (a, b, c)	10 (a, b, c)	10 (a, b, c)	10 (a, b, c)
Biomass Integrated Gasification (BIG)	Capital Cost ($/kW)	2,400 (a, b, c)	2,200 (a, c)	2,100 (a, c)	2,000 (a, c)
			2,100 (b)	1,700 (b)	1,500 (b)
	Capacity Factor (%)	80 (a, b, c)	80 (a, b, c)	80 (a, b, c)	80 (a, b, c)
	O&M ($/MWh)	12 (a, b, c)	12 (a, b, c)	12 (a, b, c)	12 (a, b, c)
	Efficiency (%)	35 (a, b, c)	35 (a, b, c)	35 (a, b, c)	35 (a, b, c)
Biomass-Rankine Cycle	Capital Cost ($/kW)	1,100 (a)	1,100 (a)	1,100 (a)	1,100 (a)
		1,100 (b, c)	1,050 (b, c)	1,000 (b, c)	950 (b, c)
	Capacity Factor (%)	80 (a, b, c)	80 (a, b, c)	80 (a, b, c)	80 (a, b, c)
	O&M ($/MWh)	10 (a, b, c)	10 (a, b, c)	10 (a, b, c)	10 (a, b, c)
	Efficiency (%)	25 (a, b, c)	25 (a, b, c)	25 (a, b, c)	25 (a, b, c)
	RO_x Removal (%)	90 (a)	94 (a)	94 (a)	98 (a, b, c)
		98 (b, c)	98 (b, c)	98 (b, c)	
Pulverized Coal Combustion	Capital Cost (US$/kW)	1,040 (a)	1,040 (a)	1,040 (a)	1,040 (a)
		1,190 (b, c)	1,190 (b, c)	1,190 (b, c)*	1,190 (b, c)*
	Capacity Factor (%)	80 (a)	80 (a)	80 (a)	80 (a)
		85 (b)	85 (b)	85 (b)	85 (b)
		40 (c)	40 (c)	40 (c)	40 (c)
	O&M ($/MWh)	9.0 (a)	9.0 (a)	9.0 (a)	9.0 (a)
		14.0 (b, c)	14.0 (b, c)	14.0 (b, c)	14.0 (b, c)
	Efficiency (%)	37 (a)	37 (a)	37 (a)	37 (a)
		36 (b, c)	36 (b, c)	36 (b, c)	36 (b, c)
Coal Advanced Combustion (ACFBC and IGCC for Local Environmental Scenario at 2015)	Capital Cost (US$/kW)	1,250 (a, b, c)	1,200 (a, b, c)	1,150 (a, b, c)	1,100
					1,400 (c)
	Capacity Factor (%)	85 (a, b)	85 (a, b)	85 (a, b)	85 (a, b)
		40 (c)	40 (c)	40 (c)	40 (c)
	O&M ($/MWh)	10 (a, b, c)	10 (a, b, c)	10 (a, b, c)	10 (a, b, c)
	Efficiency (%)	39 (a, b, c)	39 (a, b, c)	39 (a, b, c)	39 (a, b)
					43 (c)

		2000	2005	2010	2015
Diesel Engines	Capital Cost (US$/kW)	1,000 (a, b, c)	1,000 (a, b, c)	1,000 (a, b, c)	1,000 (a, b, c)
	Capacity Factor (%)	30 (a, b, c)	30 (a, b, c)	30 (a, b, c)	30 (a, b, c)
	O&M ($/MWh)	8 (a, b, c)	8 (a, b, c)	8 (a, b, c)	8 (a, b, c)
	Efficiency (%)	30 (a, b, c)	30 (a, b, c)	30 (a, b, c)	30 (a, b, c)
Residual Oil Thermal Generation	Capital Cost (US$/kW)	1,070 (a, b, c)	1,070 (a, b, c)	1,070 (a, b, c)	1,070 (a, b, c)
	Capacity Factor (%)	20 (a, b, c)	20 (a, b, c)	20 (a, b, c)	20 (a, b, c)
	O&M ($/MWh)	11 (a, b, c)	11 (a, b, c)	11 (a, b, c)	11 (a, b, c)
	Efficiency (%)	30 (a, b, c)	30 (a, b, c)	30 (a, b, c)	30 (a, b, c)
Gas Turbines	Capital Cost (US$/kW)	495 (a, b, c)	470 (a)	450 (a)	420 (a)
			460 (b, c)	420 (b, c)	380 (b, c)
	Capacity Factor (%)	92 (a)	92 (a)	92 (a)	92 (a)
		89 (b, c)	89 (b, c)	89 (b, c)	89 (b, c)
	O&M ($/MWh)	7 (a, b, c)	7 (a, b, c)	7 (a, b, c)	7 (a, b, c)
	Efficiency (%)	50 (a, b, c)	50 (a, b, c)	50 (a, b, c)	50 (a, b, c)
Hydroelectric Generation	Capital Cost (US$/kW)	1,570 (d)	1,570 (d)	1,570 (d)	1,570 (d)
		1,230 (e)	1,230 (e)	1,230 (e)	1,230 (e)
		815 (f)	815 (f)	815 (f)	815 (f)
	Capacity Factor (%)	63.5 (d)	63.5 (d)	63.5 (d)	63.5 (d)
		55.0 (e)	55.0 (e)	55.0 (e)	55.0 (e)
		53.5 (f)	53.5 (f)	53.5 (f)	53.5 (f)
	O&M ($/MWh)	4.41 (d)	4.41 (d)	4.41 (d)	4.41 (d)
		1.54 (e)	1.54 (e)	1.54 (e)	1.54 (e)
		1.29 (f)	1.29 (f)	1.29 (f)	1.29 (f)
	Construction Period (year)	2 (d)	2 (d)	2 (d)	2 (d)
		4 (e)	4 (e)	4 (e)	4 (e)
		7 (f)	7 (f)	7 (f)	7 (f)
Nuclear Generation	Capital Cost (US$/kW)	1,600 (a, b, c)	1,600 (a, b, c)	1,570 (a, b, c)	1,570 (a, b, c)
	Capacity Factor (%)	75 (a, b, c)	75 (a, b, c)	75 (a, b, c)	75 (a, b, c)
	O&M fix ($/kW)	56.3 (a, b, c)	56.3 (a, b, c)	56.3 (a, b, c)	56.3 (a, b, c)
	O&M variable ($/MWh)	0.41 (a, b, c)	0.41 (a, b, c)	0.41 (a, b, c)	0.41 (a, b, c)
	Construction Period (year)	5 (a, b, c)	5 (a, b, c)	5 (a, b, c)	5 (a, b, c)
Electricity Conservation	Levelized Cost ($/MWh)	3 (g)	3 (g)	3 (g)	3 (g)
		5 (h)	5 (h)	5 (h)	5 (h)
Transmission	Capital Cost (US$/kW/kkm)	180 (a, b, c)	200 (a, b, c)	200 (a, b, c)	220
	Capacity Factor (%)	60 (a, b, c)	60 (a, b, c)	60 (a, b, c)	60 (a, b, c)
	Loss (%)	5 (a, b, c)	5 (a, b, c)	5 (a, b, c)	5 (a, b, c)

Notes: (a) Baseline Scenario. (b) Advanced Technologies Scenario. (c) Local Environmental Control Scenario and Carbon Elimination Scenario. (d) Small hydro. (e) Medium hydro. (f) Large hydro. (g) Energy conservation in the industrial sector. (h) Conservation in other energy consumption sectors.

* Assumes that flue gas desulfurization equipment is required.

Sources: Feitoza, S., E. Serra, and M. Nascimento. 1999. Pimenta; J. 1999; De Laquil, P., M. Kearney, R. Diver, and M. Geyer. 1993; Goswami, D. 1998; Carvalho, A. 1995; Carpentieri, E., and W. Larson. 1993; EIA. 1997; and Schaeffer, R., A. Szklo, and J. Marques. 1999.

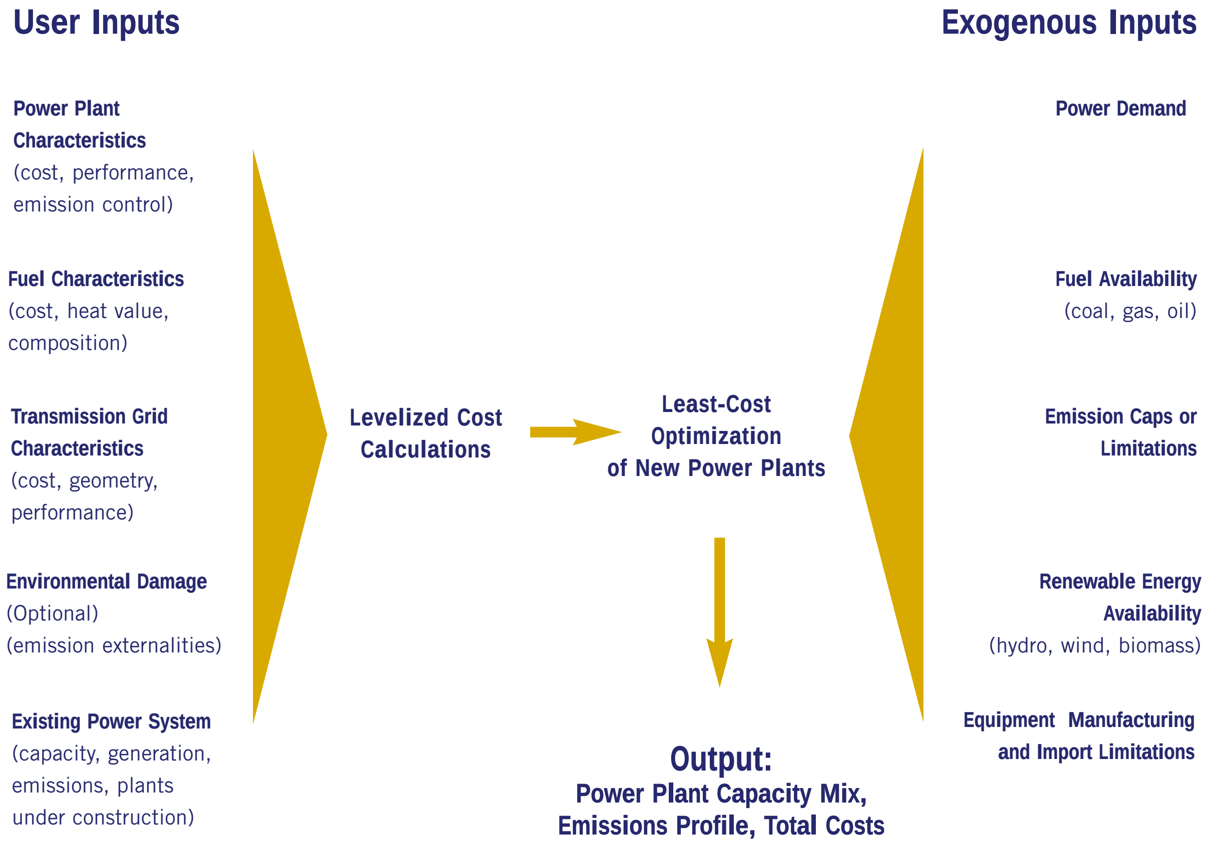
Appendix C: Specific Emissions (1)

Pulverized Brazilian Coal	Carbon (tC/TJ)		25.7
	Sulfur Content (%)		1.7
	RO_X (Particulates) (g/kWh)		0.35
	NO_X (g/kWh)		2.1
Imported Coal — ACFBC	Carbon (tC/TJ)		25.3
	Sulfur Content (%)		0.8
	RO_X (g/kWh)		0.01
	NO_X (g/kWh)		0.24
Diesel — Engine	Carbon (tC/TJ)		20.0
	Sulfur Content (%)	Baseline Scenario	1.0
		Other Scenarios, 2000-2015	0.3
	RO_X (g/kWh)		0.032
	NO_X (g/kWh)		4.68
Residual Fuel Oil — Rankine Cycle	Carbon (tC/TJ)		20.9
	Sulfur Content (%)		1.0
	RO_X (g/kWh)		0.032
	NO_X (g/kWh)		0.72
Natural Gas – CCGT	Carbon (tC/TJ)		15.2
	Sulfur Content (%)		0
	RO_X (g/kWh)		0
	NO_X (g/kWh)		0.68
Natural Gas — Fuel Cell	Carbon (tC/TJ)		15.2
	Sulfur Content (%)		0
	RO_X (g/kWh)		0
	NO_X (g/kWh)		0.01
Sugar Cane Bagasse — Rankine Cycle	Carbon (tC/TJ) (2)		0
	Sulfur Content (%)		0.2
	RO_X (g/kWh)	Baseline Scenario, 2000-2005	0.80
		Baseline Scenario, 2005-2015	0.48
		Other Scenarios, 2000-2015	0.16
	NO_X (g/kWh)		0.32
Sugar Cane Bagasse — BIG/STIG	Carbon (tC/TJ)		0
	Sulfur Content (%)		0.2
	RO_X (g/kWh)		0
	NO_X (g/kWh)		0.48
Ethanol — Fuel Cell	Carbon (tC/TJ)		0
	Sulfur Content (%)		0.2
	RO_X (g/kWh)		0
	NO_X (g/kWh)		0.05

Notes: (1) Although carbon is emitted from hydropower plant reservoirs due to the degradation of flooded biomass, these emissions are not considered in this report. First, no reliable emissions data is available; second, the amount of these emissions is minor compared to emissions from thermal plants. (2) Net carbon emissions. In the case of renewable biomass, sugar cane bagasse and ethyl alcohol, these emissions are considered to be zero.

Sources: Schaeffer, R., A. Szklo, J. Marques. 1999. *Metodologia de Elaboração de Cenários de Oferta de Energia Elétrica para o Brasil, no período 1995-2015.* COPPE/PPE/UFRJ; and "International Energy Outlook 1999."

Appendix D: The Least-Cost Model



User Inputs

Power Plant Characteristics
(cost, performance, emission control)

Fuel Characteristics
(cost, heat value, composition)

Transmission Grid Characteristics
(cost, geometry, performance)

Environmental Damage
(Optional)
(emission externalities)

Existing Power System
(capacity, generation, emissions, plants under construction)

Exogenous Inputs

Power Demand

Fuel Availability
(coal, gas, oil)

Emission Caps or Limitations

Renewable Energy Availability
(hydro, wind, biomass)

Equipment Manufacturing and Import Limitations

Levelized Cost Calculations → **Least-Cost Optimization of New Power Plants**

Output:
Power Plant Capacity Mix, Emissions Profile, Total Costs

Endnotes

1. All costs are given in 1999 U.S. dollars unless otherwise stated.

2. EIA. 1999. "Emissions of Greenhouse Gases in the United States: 1998." Energy Information Administration, November.

3. Hydropower plants do not rely on the combustion of fossil fuels — the source of most greenhouse gas emissions from the energy sector — but some additional methane and carbon dioxide emissions are produced as submerged biomass material decomposes. The amount of methane and carbon dioxide produced varies depending on local conditions. For more information, see Rosa, L. P. and R. Schaeffer. 1995. "Global Warming Potentials: The Case of Emissions from Dams." Energy Policy 23 (2): 149-158.

4. EIA. 1999. "Country Analysis Brief: Brazil." Energy Information Administration, July.

5. Income elasticity of energy (power) demand is the ratio of growth in energy (electricity) consumption to that of GDP growth. Typical industrialized countries have values close to 1 for elasticity of energy and electricity demand. The ratios are higher for industrializing countries, averaging about 1.2 for elasticity of energy demand and 1.3 or higher for elasticity of electricity demand. For more information, see Sinton, J. and M. Levine. 1998 "Energy Efficiency in China: Accomplishments and Challenges." *Energy Policy*, 26 (11): 813-829.

6. EIA. 1999. Available at http://www.eia.doe.gov.

7. This includes biomass energy, which is often ignored in primary commercial energy statistics.

8. Ministério das Minas e Energia — MME — Brasil. 1998. *Balanço Energético Nacional*. Brasília: MME.

9. Installed capacity refers to the total size of the power plants in operation. Note that capacity is related to generation through the capacity factor, or percentage of time that a plant actually produces electricity at its peak output.

10. MME. 1998.

11. Ibid.

12. Ibid.

13. Although only 8 percent of Brazilian homes did not have electricity in 1997, there are disparities in electricity services at the regional level: while 80 percent of homes in the north and northeast are not connected to the electric power grid, these services are supplied to 95 percent of homes in the rest of the country. Eletrobrás. 1998. *Plano Decenal de Expansão — 1998-2007*. Rio de Janeiro: Eletrobrás.

14. There are two other nuclear power plants still under construction: Angra II with 1,309 megawatts, which should begin operations in 2000; and Angra III, with 1,309 megawatts installed power.

15. Ministério das Minas e Energia — MME — Brasil. 1998. *Balanço Energético Nacional*. Brasília: MME.

16. Abud, A. 1999. Desvio Informal — *Uma Análise das Perdas Comerciais de Energia Elétrica no Setor Informal da Economia e em Comunidades Faveladas no Brasil*. Rio de Janeiro: COPPE/UFRJ, MSc. Thesis.

17. MME. 1998.

18. Eletrobrás was established by Law 3.890 (1961). Once established, the institutional model moved toward a natural monopoly, with Eletrobrás as the holding company. Eletrobrás controls 90 percent of electricity generation activities in Brazil.

19. This phase also features the consolidation of Eletrobrás, which became the main source of funding for the sector.

20. A series of factors prompted the crisis. These include the two oil crises that skewed the balance of payments and prompted the government to subsidize lower tariffs for electricity-intensive industries. The government also imposed controls on tariffs to keep them at levels lower than other price increases in order to curb inflation. Rosa, L. P., M.T. Tolmasquim, and J.C. Pires. 1998 *A reforma do setor elétrico no Brasil e no mundo: uma visão crítica*, Rio de Janeiro: Relume Dumará: COPPE, UFRJ.

21. Electricity tariffs are the regulated prices charged for different classes of consumers.

22. To convert from megawatt-hours to kilowatt-hours, divide by 1000. Thus, $36 per megawatt hour equals 3.6 cents per kilowatt-hour. Rosa, L. P., M.T. Tolmasquim, and J.C. Pires. 1998 "A reforma do setor elétrico no Brasil e no mundo: uma visão crítica." Rio de Janeiro: Relume Dumará: COPPE, UFRJ.

23. The average tariff was $48/MWh for the industrial sector; $98/MWh for the commercial sector; and $105/MWh for the residential sector. Eletrobrás. 1998. *Plano Decenal de Expansão - 1998-2007*. Rio de Janeiro: Eletrobrás.

24. Brazil's electric power sector is characterized by the predominance of hydropower generation, with large fluctuations in water levels in many reservoirs due to cyclic rainfall. This means that considerable investments are needed to build dams and connections between the generation and load centers.

25. Geller, H., G.M. Jannuzzi, R. Schaeffer, and M.T. Tolmasquim. 1998. "The Efficient Use of Electricity in Brazil: Progress and Opportunities." *Energy Policy* 26 (11): 859-872.

26. Bagasse refers to residual biomass material from sugar cane processing.

27. Leachate is a liquid waste, rich in organic material, created in pulp and paper production processes. It is used as a substitute for fuel oil in the pulp and paper facilities in Brazil to generate electricity.

28. Until 1997, a substantial percentage of the electricity generated at thermal power plants came from renewable biomass sources. This situation is expected to change with the start-up of the Bolivia-Brazil pipeline, which will have a maximum transportation capacity of 30 million cubic meters of natural gas per day.

29. Schechtman, R., A. Szklo, and J. Sala. 1998. *Determinação das Emissões de Carbono Derivadas do Sistema Energético Brasileiro — abordagem bottom up, Programa de Planejamento Energético/COPPE/UFRJ — Projeto BRA/95/G31 — Enabling Brazil to Fulfill its Commitments to the UN Framework Convention on Climate*.

30. Nuclear power generally does not produce carbon dioxide, sulfur dioxide, nitrogen oxide or particulate materials, and does not emit heavy metals.

31. In view of the massive development of Brazil's hydropower industry, in contrast to many other generation technologies considered here, hydropower generation costs are relatively immune to foreign exchange variations since most expenditures are necessary in Brazilian currency.

32. Eletrobrás. 1993. *Plano 2015 : Projeto 7: A Questão Ambiental e o Setor Elétrico*. Rio de Janeiro: Eletrobrás.

33. Eletrobrás. 1990. *Plano Diretor do Meio Ambiente*. Rio de Janeiro: Eletrobrás.

34. They are even more difficult to assess due to the long gap between design of a power plant and its entry into operation.

35. Rosa, L.P., R. Schaeffer, and M.A. dos Santos. 1996. "Emissões de Metano e Dióxido de Carbono de Hidrelétricas Comparadas às de Termelétricas Equivalentes," *Cadernos de Energia* 9 (1): 111-155.

36. Rudd, J.W.M., R. Harris, C.A. Kelly, and R.E. Hecky. 1993. "Are Hydroelectric Reservoirs Significant Sources of Greenhouse Gases?" *Ambio* 22(4): 246-248.

37. Gagnon, L., and J.F. van de Vate. 1997. "Greenhouse Gas Emissions from Hydro-Power — The State of Research in 1996," *Energy Policy* 25 (1): 7-13

38. The type of ecosystem flooded also affects the net carbon balance in the atmosphere since the ecosystem constituted a carbon sink prior to the reservoir's construction.

39. For a review of linear programming, see Bertsimas, D., and J. Tsitsiklis. 1997 *Introduction to Linear Optimization*. Athens: Athena Scientific.

40. Levelized cost analysis, also referred to as lifecycle costing, spreads costs out over the economic lifetime of a plant, allowing direct comparisons of cost per kilowatt-hour of delivered power.

41. Energy conservation is addressed in this study as an energy "supply" option.

42. Eletrobrás. 1998. *Plano Decenal de Expansão — 1998-2007*. Rio de Janeiro: Eletrobrás.

43. Use of the elasticity in electric power consumption over GDP for the market forecast is somewhat problematic because there is an inertial component in electric power consumption that prompts growth even at times of crisis or low economic growth. In Brazil, there are still many homes the electricity network does not service. Repressed demand for household appliances engenders high consumption growth rates for the residential sector, regardless of the variation in GDP.

44. Some noteworthy projects under way at the development stage are: the Itá hydropower plant (1,450 MW), scheduled to begin operations in 2000, and the Machadinho hydropower plant (1,140 MW), scheduled to begin operations in 2003. Projects for which entrepreneurs already have concessions and licenses include the expansion of Itaipu (1,400 MW), scheduled for 2001, and the Lajeado hydropower plant (850 MW), scheduled for 2004.

45. Note that coal and natural gas prices are expected to remain essentially unchanged through 2015, while petroleum prices are expected to rise slowly. Market reform and improved technologies will put downward pressure on the price of coal and natural gas in Brazil. The authors believe that petroleum prices will rise due to the greater instability in the market for this form of energy.

46. Zylbersztajn, D., S. Coelho. 1993. *Colheita Mecânica de Cana e Economicidade da Cogeração*. Anais do VI Congresso Brasileiro de Energia. Rio de Janeiro.

47. Tudera, M., S. Guerra, R. de Almeida. 1997 "Alocação da Renda Gasífera: Uma Análise do Gasoduto Brasil-Bolívia." *Revista Brasileira de Energia* 6(2).

48. Schaeffer, R., M. Tolmasquim, A. Szklo, and M. Tavares. 1999. *Impactos da Liberação da Importação de Derivados sobre a Indústria de Refino Nacional*. Rio de Janeiro: ANP/COPPE/UFRJ.

49. Some states in the United States are required to use shadow environmental externality costs in their planning analysis. These values range from $0-23,000 per ton of sulfur dioxide, $0-31,500 per ton of nitrogen oxide, and $0-4,554 per ton of suspended particulates. For a more complete discussion of how environmental externalities are calculated, see EIA. 1995. Electricity Generation and Environmental Externalities: Case Studies. Washington, DC: US Department of Energy, Energy Information Administration.

50. In Bernstein et al., "Developing Countries and Global Climate Change: Electric Power Options for Growth," the corresponding values for sulfur dioxide, nitrogen dioxide, and particulates ranged from $130-240, $430-2,200, and $170-1,130 per ton, respectively. In Chandler et al., "China's Electric Power Options: An Analysis of Economic and Environmental Costs," sulfur dioxide values used ranged from $180 to $960 per ton.

51. Geller, H., G.M. Jannuzzi, R. Schaeffer, and M.T. Tolmasquim. 1998. "The Efficient Use of Electricity in Brazil: Progress and Opportunities." *Energy Policy* 26 (11): 859-872

52. This scenario assumes that certain hydropower plants have adverse effects due to their low ratio of power density to flooded area. This indicator (W/m^2 reservoir) establishes a basis for analysis. The national average for power plants in operation stands around 6.3 W/m^2. The carbon elimination scenario assumes that only plants with power density higher than 6.5 W/m^2 can be built, consequently reducing the hydropower potential available under this scenario.

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