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EVALUATION OF ALTERNATIVE FUTURE ENERGY SCENARIOS FOR BRAZIL USING AN ENERGY MIX MODEL

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ABSTRACT

The accelerated growth of the energy market that is being observed in Brazil requires a deeper understanding of Brazil's long-term energy demand and prospects. To avoid possible problems with respect to resource allocation and environmental discharges, alternative scenarios for future energy production and consumption should be identified and evaluated. This study models and assesses the performance and the emissions impacts of electric energy technologies in Brazil, based on selected economic scenarios, for a time frame of 40 years, taking the year of 1995 as a base year. A Base scenario has been developed, for each of three economic development projections, based upon a sectoral analysis. Data regarding the characteristics of over 300 end-use technologies and 400 energy conversion technologies have been collected. The stand-alone MARKAL technology-based energy-mix model, first developed at Brookhaven National Laboratory, was applied to a base case study and an alternative case study, for each economic scenario, assuming an increase in thermoelectric contribution to the power production system by 20 percent at 2010. Results such as the distribution of fuel use for power generation, electricity demand across all sectors of the economy, total CO_2 emissions, use of renewables for electricity production, and others, are evaluated. For instance, CO_2 emissions from burning fossil fuels for power generation in 2035 is estimated to be 180,000 tonnes in the minimum economic growth base scenario and 3,000,000 tonnes in the maximum economic growth base scenario. Similarly total electricity output rises from 12,000 PJ to 73,000 PJ, respectively. This paper provides an overview of the methodology, illustrative results, and recommendations regarding energy development priorities for Brazil.

Keywords: MARKAL, energy modeling, energy planning, reduction of GHG analysis.

1.0 INTRODUCTION

The share of global energy consumption by developing countries has increased rapidly; therefore, a deeper understanding of their energy demand and prospects is essential for a better grasp of likely changes in the global energy market.[1]

Although per capta levels of greenhouse emissions from energy use are much lower in developing countries than in the industrial countries, the developing countries rapid population and economic growth will increase their share of total energy use and emissions in the future[2].

The accelerated growth of the energy market that is being observed in Brazil, resulting from the stabilization of the economy, is stimulating the search for projects that would provide an increment to the energy supply, especially electricity supply, in the short and long term. ELETROBRAS estimates that approximately 30,000 MW of new generating capacity will be necessary over the next 10 years, requiring an investment of approximately $20 billion. Therefore, a deeper understanding of Brazil's energy demand and prospects is essential for a better grasp of the changes likely in the global market, as well as to take advantage of opportunities to respond to the needs with reasonable costs and environmental impact. Among the options for the expansion of the electric system, Brazilian government is considering thermo power plants using natural gas as fuel.

Studies of Brazilian energy development are being conducted by some agencies, focusing on the current state of the system, identifying potential for energy production and savings, and dealing with a relatively short projection period.[3,4,5] Usually, these studies present an overall picture of the Brazilian energy system and provide a basis for decision-makers to schedule future development. However, economic analyses of system development have not been conducted, nor has uncertainty in the results been considered. Also, these studies do not consider the details of end-use technologies, which is one major determinant of energy demand.

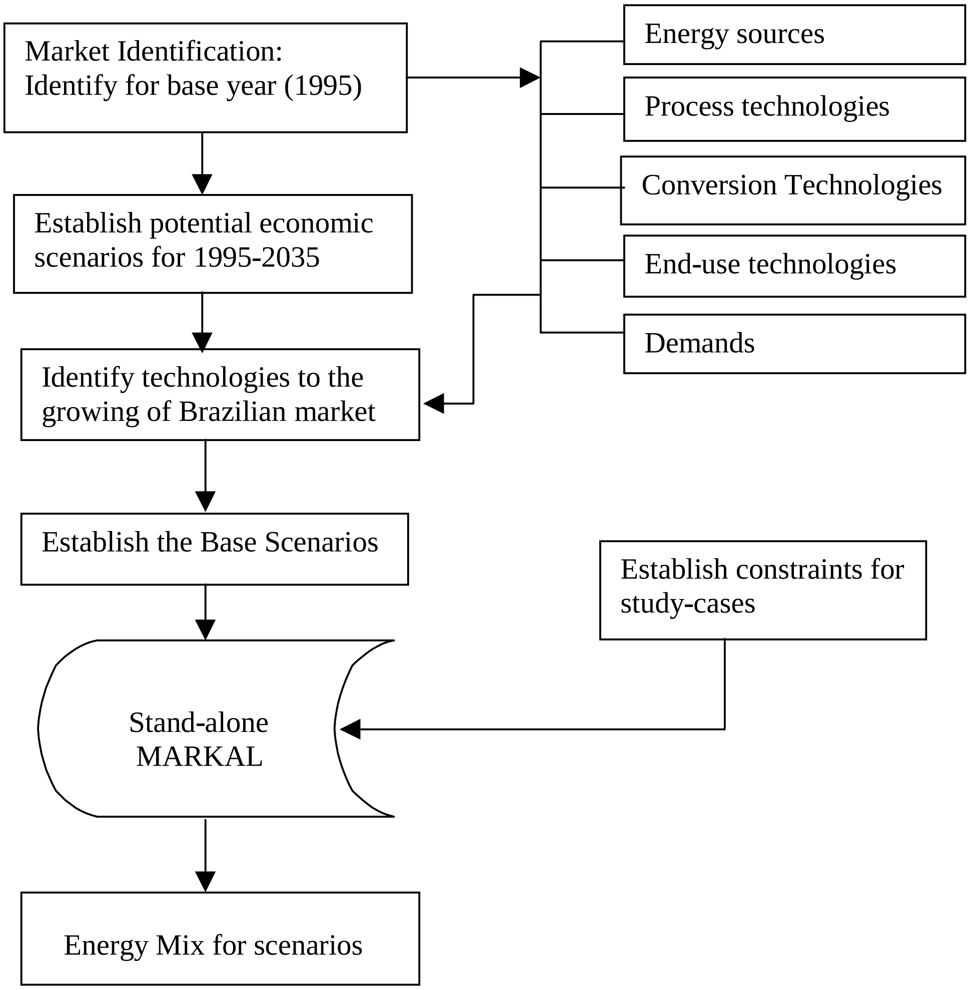
Renewable energy, such as biomass and wind energy, which may be important in the future of Brazilian energy development, is not included when projections of energy supply and demand are made for Brazil. Also, CO_2 emissions from energy use are not a concern in energy projections. However, it is important to figure out ways to better develop the system and reduce CO_2 emissions, as established in UN Framework Convention on Climate Change (FCCC), since it is the most important greenhouse gas. To project future energy needs, it is important to employ an integrated assessment framework in which relationships between energy sector development and overall economic development, and the impact of energy development on CO_2 emissions, are considered.

The main objective of this paper is to establish a methodology to develop a technology database to be used by an energy mix model, such as the stand-alone mode of MARKAL, in different case studies in Brazil. This paper focuses on electricity in order to be able to answer questions such as: (1) what technologies will be used to meet electricity demand, 40 years ahead, for different economic scenarios? and (2) if the contribution of thermoelectric power to the electric system grows to 20 percent in the next 15 years, what will be the least-cost solution for this expansion and the net change in CO_2 emissions? The answer to these questions will provide insights to the new agents from the private sector in the Brazilian power sector. The privatization process that recently started in Brazil requires the identification of alternative scenarios for the future in terms of costs and benefits, as well as least cost solutions for options and strategies. It is also important to identify cost-effective responses to restrictions on emissions when analyzing long-term energy balances under different scenarios.

2.0 OVERVIEW OF METHODOLOGY

The overall methodology for this research is an integrated consideration of electric technologies for power generation, Brazilian market characteristics and uncertainties associated with technology performance, emissions and cost, to provide a "least-cost" mix of energy technologies to meet a specified demand. A diagram illustrating the major components of the methodology and functional modeling steps used in this research is given in Figure 1.

Figure 1. Methodology Diagram



2.1 Market Identification

Key characteristics of the Brazilian market, such as capital availability, resource base, growth rates, environmental constraints, sectoral energy demand, and others, have been quantified.

These characteristics are taken into account by the energy-planning model, and the diversity in energy technology needs will be based on that.

2.2 Establishment of Potential Scenarios

After assembling data which adequately characterize the present state of the market relative to sectoral energy demand and to supply constraints, scenarios are applied to potential future events to determine alternative outcomes of market-specific costs and constraints that affect energy demand and the choice of technology options.

Three scenarios for the 1995 to 2035 time period were developed. A World Bank projection of the Brazilian population is assumed in all three cases.[6] Three economic growth cases assumed are: (1) a minimum growth case (Caaetê) projected by the Subsecretary of Analysis and Evaluation of the Brazilian Government (SAE); (2) an intermediate growth case projected by this study using time series analysis; and (3) a maximum growth case (Abatiapé) projected by SAE.[7]

2.3 Identification of Technologies for Power Generation and their Environmental Impacts

A large number of technology options can be considered for power generation. Therefore, initially we can identify generic technologies and their attributes, such as: emissions, efficiency, and cost. Later, the main criteria for identifying technologies of potential importance will be: (1) the potential for the technology to make a significant impact in meeting energy or end-use needs in Brazil during the time period of interest; and (2) the potential for significant improvements in the technology, such as efficiency improvement. A report prepared for Working Group II of the Intergovernmental Panel on Climate Change presents an inventory containing information on technologies, methods, and practices that can help to limit emissions of greenhouse gases.[8] The inventory contains information for each technology on performance characteristics and applications, capital and operating cost, emissions, and infrastructure requirements. This inventory, as well as studies made by ELETROBRAS, was used to identify potential technologies for power generation for the expansion of the Brazilian electric system.[4]

2.4 Identification of End-Use Technologies by Economic Sector

A set of 345 end-use demand technologies has been identified for all economy sectors, including lighting, process heat, direct heat and motive power technologies. To each demand technology a group of energy carriers is assigned, forming a Reference Energy System (RES). To each economic sector, a RES is established, and all information needed about the 345 end-use demand technologies, such as energy efficiency, capacity and costs, are listed. Energy efficiency is defined as the percentage ratio of useful energy output to input energy. For instance, the efficiency of a furnace with capacity of burning 600 ft^3/h, using natural gas with a heating value of 1000 BTU/ft^3 as fuel, and a furnace output of 500,000 BTU/h, is estimated to be 83.3 percent. As another example, for lighting, efficacy is used instead of efficiency. It is expressed as lumens per watt, which means the ratio of light from a lamp to the electrical power consumed.

2.5 Establishment of Base Scenarios

The base scenarios are constructed according to the expected demands for energy services. These demands are projected according to the GDP growth rates or GDP per capita growth rates, obtained from the economic scenarios previous established. A total of three Base scenarios are obtained, one for each economic scenario.

2.6 Market Detailed Evaluation Using MARKAL model

Detailed evaluation of energy-mix options for Brazil was done using the stand-alone mode of MARKAL ("MARKet ALlocation") model. MARKAL is a large-scale linear programming optimization model, first developed in the 1970s at Brookhaven National Laboratory to support strategic energy planning. It is widely used in the international community for integrated analysis of environmental options, such as reduction of greenhouse gas emissions, and to explore mid- to long-term responses to different technological futures, emissions limitations, and policy scenarios.[9,10]

In MARKAL, an energy system is represented as a set of energy technologies that extract, transport, convert and use energy.[11] MARKAL captures the complex interrelationship of energy systems from primary energy supply to energy service demands and optimizes the given energy system by minimizing cumulative system cost over several time periods. It is also designed to enable the evaluation of the impacts of controlling energy use related to environmental pollutants, such as CO_2, SO_2, NO_x, and to heat emissions and land use.

In MARKAL, the energy system is represented by energy carriers and individual devices at every stage of the extraction, transformation, distribution and consumption of energy forms. The model includes four technology classes: (1) energy sources; (2) transformation processes; (3) conversion processes; and (4) demand technologies. These technologies are explicitly described in the model in terms of their technical and economic coefficients. This feature allows the model to be readily applied to technology assessment.[12] The representation of electricity generation and process technologies in MARKAL includes investment, capacity, and production. End-use demand technologies are modeled by investment and capacity variables. For end-use technologies, production is assumed to be equal to capacity.

3.0 CHARACTERISTICS OF THE BRAZILIAN ENERGY SYSTEM

This section discusses the major primary and secondary energy sources used in Brazil, the electricity generation system, and CO_2 emissions.

3.1 Primary and Secondary Energy Consumption in Brazil

According to the Brazilian Energy Balance 1999, prepared by the National Department for Energy Development of the Secretary for Energy of the Ministry of Mines & Energy, Brazil consumed approximately 228 Mtoe of primary and secondary energy sources in 1998.[13]

Table 1 lists the most important sources based on their share of total energy use. Currently, Brazil is experiencing an excess supply of natural gas with the creation of pipelines to import gas, further development of domestic sources, and the delay in the construction of several gas-fired power plants. Brazil has minor coal reserves of poor quality and imports metallurgical coal for its steel industry, with a small portion burned to generate electricity.[13,14] Firewood is used in Brazil mainly by rural residential and agricultural sector. Sugar cane and its sub-products, such as cane juice, molasses and sugar cane bagasse, are used mainly by the industrial sector. Most gas and coal coke, as well as charcoal, is used in the pig iron and steel industry. Anhydrous alcohol is used as an additive to gasoline, and hydrated alcohol is used in its pure state in specially designed car engines. Most petroleum derivatives are used for transportation. The major consumer of electricity is the industrial sector followed by the residential sector.

Table 1. 1998 Brazilian Energy Consumption

Sources	**Share of Total Final Energy Use (%)**
Natural Gas	2.2
Mineral Coal	1.0
Firewood	5.7
Sugar Cane Bagasse	7.4
Other Primaries	1.1
Gas Coke	0.6
Coal Coke	2.8
Electricity	39.0
Charcoal	1.8
Ethyl Alcohol	3.1
Petroleum Derivatives	35.2
Other Secondaries	0.1
TOTAL	100.0

Source: Brazilian Energetic Balance – BEB – 1999.[13]

3.2 The Existing Brazilian Electricity Generation System

Detailed information about the Brazilian electricity system is required in order to establish the approach for modeling the system, and to aid identifying potential for change.

The Brazilian Electricity System is currently divided into three separate sub-systems, as follows.

a) **South/Southeast/Midwest Interconnected System** had an installed capacity of 42,706 MW in December 1997, considering only 50 percent of Itaipu Binational Hydropower Plant's installed capacity of 6,300 MW, and is composed of 191 hydropower plants (39,275 MW) and 24 thermoelectric plants (3,431 MW).

b) **North/Northeast Interconnected System**, which corresponds to markets in the lower Tocantins, Belém and Tucuruí Hydropower Plant regions, and to the entire Northeast Region, had an installed capacity of 14,686 MW in December 1997. It is comprised of 17 hydropower plants (14,387 MW) and 3 thermoelectric plants (299 MW).

c) **Isolated Systems**, which correspond to 300 locations that are electrically isolated from the remainder, are in the majority of the North Region. Among them, the following systems supplying state capitals can be highlighted because of their size: Boa Vista, Macapá, Manaus, Porto Velho and Rio Branco. The combined installed capacity of the Isolated Systems was 1,932 MW in December 1997, of which 1,367 MW correspond to thermoelectric plants and 565 MW to hydropower plants.

The North/South connection was powered up in December 1998. This connection is between the North/Northeast System and the South/Southeast/Midwest System, by means of a transmission line between Imperatriz (Maranhão) and Serra da Mesa Hydropower Plant (Goiás), using alternating current at 500 kV and having a length of approximately 1,279 km.

Based on the information here described it is possible to assume that the country has an interconnected electricity system, since the isolated system represents only 3.2 percent of the total. It is also clear that the country is currently mainly supplied by hydropower, which is a constraint in the future energy mix.

3.3 CO_2 Emissions from Energy Use

Total carbon emissions from burning fossil fuels are usually very low in developing countries such as Brazil. However, as a result of economic growth and changes in the energy production system, such as an increase in the thermal contribution to electricity production, there may be a dramatic increase in those emissions.

A comparison of 1995 carbon emissions from burning fossil fuels among some emerging and OECD countries showed that Brazil had the smallest CO_2 emission intensity (0.33 kg CO_2/US\$GDP) and the greatest emission share in the transportation sector (41.5 percent), among the countries compared.[15]

Although carbon emissions in Brazil have remained fairly steady, improvements in energy efficiency and an increased use in renewable resources may be considered, that could lead to a reduction in air pollution and a subsequent improvement in living conditions. However, an increase in the use of fossil fuels in Brazil could lead to higher CO_2 emissions.

4.0 SCENARIOS

Estimates of possible future economic development are usually the first step when evaluating future energy system development and are frequently established through scenarios. First, this section examines briefly the history of economic development in Brazil, and then presents scenarios of future economic growth. The scenarios for economic growth are based on the scenarios for GDP and population.

The Brazilian populational growth rate decreased from 3 percent per year during the sixties to 1.6 percent per year during the nineties.[16] With a population of over 160 million, a land area only slightly smaller than the United States, and economic output of nearly US$800 billion, Brazil ranks as one of the largest countries in the world.[17]

SAE has been working on the establishment of scenarios as a reference for long-term national estimates of development.[7] Those scenarios received Brazilian indigenous names; however, there is no relation between the scenarios and the meaning of the names. The national scenarios

Abatiapé and Caaetê represent different situations and represent possible trends for the future of Brazilian environment. In the Abatiapé scenario, which is the maximum growth case, the State preserves its capacity of governing, with focus on: (1) political, economic, and social stability; (2) public investments addressed to the modernization of economy; (3) high growth rates; and (4) a greater insertion into world trades. In the Caaetê scenario, which is the minimum growth case, the international market is characterized by a strong financial and commercial unbalance, negatively affecting the development of the country.

A new scenario was projected in this work, in which the autoregressive integrated moving average (ARIMA) model-building approach, proposed by Box and Jenkins for forecasting, is applied to GDP growth rates.[18,19] The SAS System for Forecasting Time Series (SAS/ETS) software, developed by SAS Institute Inc., was used.[20] This scenario represents an intermediate growth case.

The scenarios for Brazilian economic development, proposed by this study, are summarized in Table 2, and are used to develop scenarios for energy service. Toward the end of the forty-year period, the Abatiapé scenario represents approximately four times the economic activity of the ARIMA scenario, and approximately eight times the economic activity of the Caaetê scenario. Therefore, there is substantial variability in economic activity reflected in the comparison among the three scenarios. Although it is possible that none of these scenarios may capture what will actually happen, the use of three very different scenarios as the basis for analysis is a means for attempting to deal with uncertainty regarding future economic activity.

Table 2. Expected Scenarios for Brazilian Economic Development: 1995 – 2035

	Population[a] (Million)	GDP – Caaetê[b] (US$Billion)	GDP – ARIMA (US$Billion)	GDP – Abatiapé[c] (US$Billion)
1995	156	728	728	728
2000	172	832	826	859
2005	183	1001	1030	1266
2010	194	1109	1305	1921
2015	205	1262	1658	3010
2020	215	1476	2108	4717
2025	224	1726	2678	7393
2030	231	2019	3404	11585
2035	238	2361	4325	18154

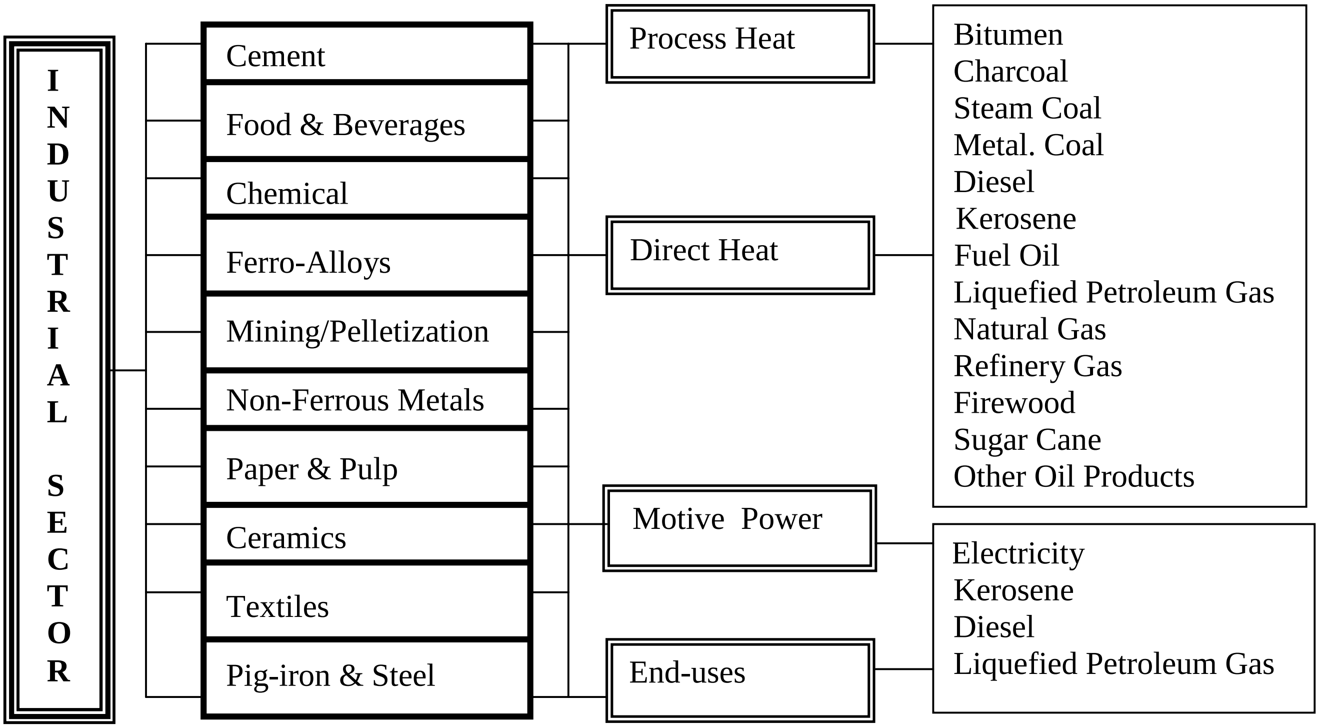
Source: (a) World Bank[1], (b,c) SAE[7]

5.0 THE REFERENCE ENERGY SYSTEM AND DATA BASE ACCORDING TO ECONOMIC SECTORS

A Reference Energy System (RES) is used to represent the energy system in a specific economic sector, depicting flows of energy from resource through end-use devices to demand for useful energy services in an economic sector. Each link in the RES is characterized by a set of technical coefficients (e.g., efficiency), environmental emission coefficients, if applicable (e.g., CO_2, SO_2, and NO_x), and economic coefficients (e.g., capital costs).

Figure 2 shows the Reference Energy System (RES) for Brazilian industrial sector as an example. The ten most important subsectors are listed, as well as all energy sources (e.g., diesel, kerosene, natural gas) used by each end-use device that will provide the required energy demand (e.g., process heat, motive power). In this sector, thirteen different fuels are considered for providing process and direct heat, and four different fuels are considered for motive power and other end-uses. A total of 340 end-use technologies are defined for all subsectors. Examples of economic sector and end-use technologies are given in Section 5.1. A similar RES was made for each economic sector, in order to identify all important flows of energy.

Figure 2. Example of a Reference Energy System Diagram for a Specific Economic Sector



5.1 Projection of Useful Energy Demands

The economic sectoral demand categories were defined according to those included in the Brazilian Useful Energy Balance, including:[21]

a) **Residential sector.** End-uses include: lighting, cooking, refrigeration, water heating, air conditioning, and other electric and electronic appliances.
b) **Industrial sector.** Divided into ten subsectors corresponding to: Cement, Food and Beverage, Chemical, Ferro-Alloys, Mining and Pelletization, Non-Ferrous Metal, Paper

and Pulp, Ceramics, Textiles, and Pig-Iron and Steel Industry. For each sector the end-uses considered were motive power, direct heat, process heat and other end-uses.

c) **Transport sector.** Different transport ways considered were terrestrial (vehicle and trains), aerial, and maritime, each for passengers and for freight.
d) **Commercial and Public sectors.** This sector includes: commercial activities, restaurants and hotels, services, and public lighting. The considered end-uses are lighting, process heat, direct heat, and other end-uses.
e) **Agricultural sector.** This sector includes activities related to crops and processing of agricultural products, and end-uses such as process heat, direct heat, motive power, and other end-uses.
f) **Energy sector.** The consumption of energy in the energy sector is centered, largely, in two areas: Petroleum Refineries and Alcohol Distilleries. The end-uses considered are process heat, direct heat, motive power, and other end-uses.

Motive power includes electric motors and motors using fuels such as gasoline, kerosene, diesel and others.

Direct Heat is one of the most frequent energy applications and one of the more diverse. For each sector and for each fuel, direct heat performs differently with different efficiencies. For instance, in the residential sector, direct heat is used for cooking, heating and clothes drying machines. In the agricultural sector it is mostly used to promote dry alimentary products, in order to increase stock capacity. In the industrial sector, direct heat using electricity is important for the metallurgic industry, and direct heat using other fuels is important for the cement, ferro-alloys, pig-iron and steel, and ceramic industries.

The use of energy in process heat includes vapor generation, water heating, and thermal fluids heating. In the residential sector, for instance, common end-use equipment in Brazil is an electric shower-bath nozzle used to heat water. In the industrial sector, boilers using different fuels are used in different activities.

Other end-uses include computers, TV receptors, copy machines, telecommunications equipment, and many others.

The process of estimating useful energy demands requires knowledge of the base year useful consumption. For that it is necessary to access final energy consumption data and the available information about the efficiency of end-use devices. Useful demand projections are then made according to a proposed procedure. In this study, GDP growth rates were used to forecast useful demands in the industrial, agricultural, commercial, and energy sectors. For the residential and transportation sectors, useful demand scenarios were developed based on GDP per capita growth rates. A total of three sets of demand scenarios were established according to each of the three economic scenarios.

5.2 End-Use Demand Technologies

Different end-use technologies, existing and new-ones, are included in the analysis. End-use technologies are modeled in MARKAL based upon their investment and capacity characteristics.

These characteristics are described by technical parameters such as efficiency, useful life, residual capacity, average utilization factor, capacity bounds, and economic information, such as investment cost, fixed operation and maintenance cost, fuel delivered costs, and investments bounds. Table 3 shows an example of technical parameters required to specify an end-use demand technology. The wood boiler in the example, used in the agricultural sector, is assumed to have a upper capacity bound of 22.4 PJ, which means that the installed capacity is limited to this maximum value for the time period considered. The boiler has an energy efficiency of 60 percent and a lifetime of 30 years. It is considered to have an average-utilization factor of 1, and the costs related to investment in new capacity, fixed operation and maintenance, as well as the delivery cost of the fuel used are listed in units of US$million per PJ.

Table 3. Example of Technical Parameters for an End-Use Demand Technologies, for a Specific Time Period: Wood Boiler Process Heat for Agricultural Sector

Parameter	Parameter Description	Value
BOUND (BD)	Bound on Capacity (PJ/year) - Upper	22.4
CF	Annual Utilization (decimal fraction)	1
DELIV(ENT)	Annual Delivery Cost (US$million/PJ)	0.55
EFF	Technical Efficiency (PJ/PJ)	0.6
FIXOM	Annual Fixed O&M Costs (US$million/PJ/year)	.45
INVCOST	Total Cost of Investment in new capacity (US$million/PJ/year)	4.65
LIFE	Lifetime of New Capacity (years)	30

Source: BEU-MAPEE[21] , BEB 1999[13] , Ministério da Indústria e Comércio (personal comunication)

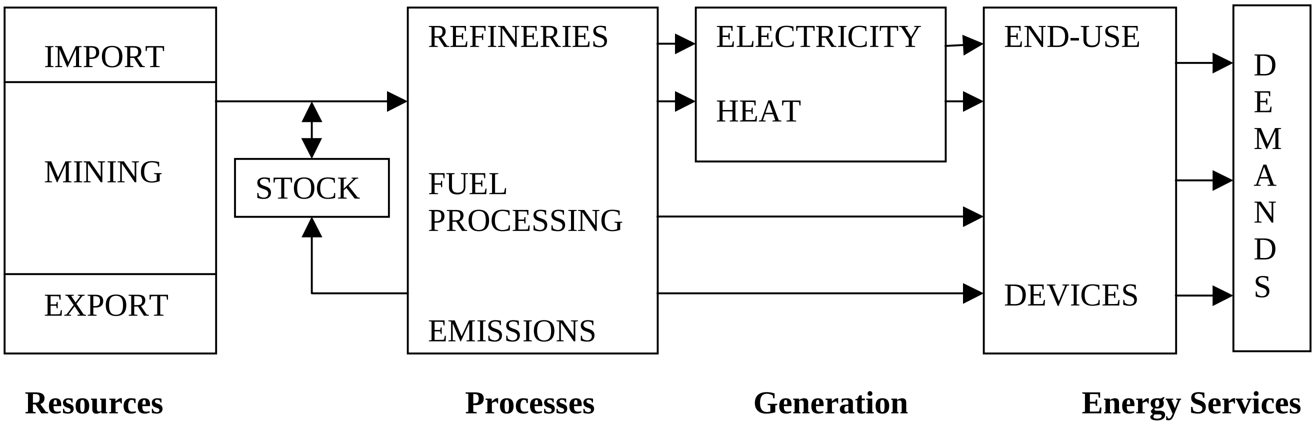
It should be noted that bounds on capacities or activities are usually used for the base year, where the real value of the parameter is known. For the time periods in the future no bounds are assumed in order to allow the model to choose the amount to be produced.

The information obtained about all end-use technologies used by all economic sectors, as well as the projected demands for energy services, is integrated to MARKAL according to the reference energy system described in the next section.

6.0 THE STAND-ALONE MARKAL REFERENCE ENERGY SYSTEM AND DATA BASE

The base of a MARKAL model is a network describing the structure of an energy system as interconnected flows of fuels, through energy-producing and energy-consuming technologies, and specified energy demands. The block diagram represented in Figure 3 illustrates the stand-alone MARKAL Reference Energy System.[22]

Figure 3. MARKAL Reference Energy System (stand-alone mode)



6.1 Energy Sources

MARKAL has three sources of primary fuels including imports, mining/extraction, and stocks, and one sink in exports. Each resource is described according to its maximum amount availability as a function of cost and time, and its environmental characteristics. Export and import fuels are defined according to international trade for primary and secondary energy sources. For instance, Brazil imports coal from the United States, Australia, Poland and Canada, as well as crude oil from Venezuela and Argentina and natural gas from Bolivia.

Table 4 shows an example of technical parameters required to specify a resource technology. In this example, the natural gas mining technology activity, which represents one of the existing plants in the country, has an upper bound of 75.78 PJ. This bound means that the production is limited to this maximum value for the time period of 1995 considered in this example. As explained before, this bound is usually used for the base year only. The natural gas extraction plant has an operating cost of US$ 2.45 million per PJ. The CO_2 emissions associated only with extraction are 12,500 tonnes per PJ of gas extracted. Total resource availability of 12,938 PJ means the total availability of energy carrier over the entire time horizon.

Table 4. Example of Technical Parameters for a Resource Technology for a Specific Time Period: Natural Gas Extraction Plant

Parameter	Parameter Description	Value
BOUND (BD)Or	Bound on Activity (PJ) - Upper	75.78
COST	Annual Resource Cost (US$million/PJ)	2.45
ENV_SEP	Emissions Coefficient (thousand tonnes/PJ)	12.5
CUM	Total Resource Availability (PJ)	12,938

Source: BEB 1999[13], ANP – Agência Nacional do Petróleo (Personal Communication).

Solar, geothermal, and wind energy used by renewable technologies in conversion processes are also considered energy sources by MARKAL. However, no resource technology needs to be specified to produce them since they are provided by nature and are considered inexhaustible.

6.2 Process Technologies

All the energy transformation processes different from those producing electricity and low-temperature heat are grouped in MARKAL under the “process” class. This class includes the petroleum refinery process, natural gas plants, gasification plants, coking plants, charcoal plants, nuclear cycle and other processes.

The technologies are modeled by three sets of parameters: investment, capacity, and production or activity. Technical parameters include efficiency, useful life, residual capacity, availability factor, capacity, and production bounds. Economic parameters include investment cost, fixed and variable operation and maintenance costs, fuel delivery costs, and expansion or investments bounds.

Table 5 shows an example of technical parameters required to specify a process technology. The refinery process in the example, which represents one of the existing refineries in the country, is assumed to have a maximum installed capacity of 105.54 PJ for the time period of 1995 considered in this example, and a lifetime of 50 years. Annual availability means hours of production availability divided by the number of hours in a year. This entry should account for both forced and scheduled outages during the entire year. The costs related to investment in new capacity, fixed operation and maintenance, as well as the delivery cost of the fuel used are listed in units of US$million per PJ. The fractions of products produced are also listed.

Table 5. Example of Technical Parameters of a Process Technology: Refinery Process

Parameter	Parameter Description	Value
AF	Annual Availability (Decimal fraction)	1
BOUND (BD)	Bound on Capacity (PJ/year) - Upper	105.54
DELIV(ENT)	Annual Delivery Cost (US$million/PJ)	.235
INVCOST	Total Cost of Investment in new capacity (US$million/PJ/year)	1.64
OUT (diesel)	Energy Carrier Output (PJ/PJ)	.135
OUT (fuel oil)	Energy Carrier Output (PJ/PJ)	.024
OUT (gasoline)	Energy Carrier Output (PJ/PJ)	.098
OUT (liquefied gas)	Energy Carrier Output (PJ/PJ)	.024
OUT (naphtha)	Energy Carrier Output (PJ/PJ)	.022
FIXOM	Annual Fixed O&M Cost (US$million/PJ)	.178
LIFE	Lifetime of New Capacity (years)	50

Source: BEB 1999[13] , ANP – Agência Nacional do Petróleo (Personal Communication).

6.3 Conversion Technology

Electricity is modeled in MARKAL under the “conversion” class and through its investment, capacity and production or activity parameters.

In the Brazilian case, the conversion technologies were divided to existing and future technologies. The existing technologies include hydroelectric plants of different capacities, coal plants, natural gas turbines, diesel oil plants, wind power plants, nuclear plants, and cogeneration plants. The future technologies include the plants under construction, the ones in which the project is already approved and construction already scheduled, and potential future technologies, such as biomass combined cycle, natural gas combined cycle, and solar energy technologies.

Table 6 shows an example of technical parameters required to specify a conversion technology. The natural gas conversion technology in the example, which represents one of the existing plants in the country, is assumed to have an upper capacity bound of 80 MW for the time period of 1995 considered in this example, a lifetime of 20 years, and it is scheduled to stop around 36 days per year for maintenance. The costs related to investment in new capacity, fixed operation and maintenance, as well as the delivery cost of the fuel used are listed in units of US$million per GW. The combustion emission coefficients are listed for CO_2, NO_x, and SO_x. The parameter INP(ENT) is defined as the inverse of the thermal efficiency of the technology, that is calculated on the basis of energy carrier input per PJ of electricity produced.

Table 6. Example of Technical Parameters of a Conversion Technology for a Specific Time Period: Natural Gas Combined Cycle Gas Turbine

Parameter	Parameter Description	Value
AF	Annual Availability (Decimal fraction)	.9
BOUND (BD)	Bound on Capacity (GW) - Upper	.08
DELIV(ENT)	Annual Delivery Cost (US$million/PJ)	0.14
ENV_ACT (CO2)	Emissions Coefficient (thousand tonnes/PJ)	165.28
ENV_ACT (NOx)	Emissions Coefficient (thousand tonnes/PJ	.667
ENV_ACT (SOx)	Emissions Coefficient (thousand tonnes/PJ	.0009
FIXOM	Annual Fixed O&M Costs (US$million/GW)	15.55
INP(ENT)	Energy Carrier Input (PJ input/PJ output)	3.33
INVCOST	Total Cost of Investment in new capacity (US$million/GW)	622.00
LIFE	Lifetime of New Capacity (years)	20

Source: Ten-Year Expansion Plan (1998/2007) – ELETROBRAS, CNEN – Comissão Nacional de Energia Nuclear (personal communication)

7.0 EXAMPLE APPLICATION OF MARKAL MODEL

This example application is intended to provide a brief idea about the kind of information the user will be able to get from the stand-alone of MARKAL results, even though the model output includes nineteen MARKAL results tables and some 220 results parameters.

Once the database with the technical and economic information on the resource technologies, end-use technologies, process and conversion technologies is completed, and the useful demands are defined, MARKAL can be run.

In order to run MARKAL, a Pentium III 650 MHz personal computer with 128 MB of SDRAM was used, taking approximately 12 minutes for each run. A total of six cases were executed. For each of the three economic scenarios, a base and an alternative scenario were obtained. First the model was executed with no constraint, which means that the model is free to choose the set of technologies that will provide the least cost solution for the system. The alternative scenario was the one in which the model forces an increase in the thermal contribution to the power production system to at least 20 percent in 2010. A constraint in which the total electricity produced by thermal power plants fueled by natural gas, coal, diesel and fuel oil has to be at least 20 percent of the total electricity produced by the system, was added to the base scenario. The total electricity is comprised by the amounts produced by thermoelectric plants, hydroelectric plants, nuclear plants, and plants using renewables. The alternative scenario is based upon a policy option considered by the Brazilian government, in which thermoelectricity will be strategically important for the time when the hydropower potential becomes less competitive, due to the cost of the plants or their great distance from the centers of consumption.

The results of the six scenarios, including three base scenarios and three alternative scenarios, and data for the base year of 1995, are summarized in Table 7. However, this is only a small portion of the total results provided by the model, which includes result parameters such as: useful energy by demand devices, shadow prices of energy carriers and emissions, reduced costs of technologies, and many others. As the objective was to analyze the behavior of the electric system under different situations, only parameters related to this issue were chosen to be listed.

The six case studies represent variation of two major assumptions. The first is regarding economic growth, and the second is regarding the share of thermal electric power plants. The case study results imply that uncertainty in most results is driven more by uncertainty regarding economic growth than by a decision to require a minimum market share for thermal power plants. For example, the total electricity output in 2030 for each of the three economic scenarios is approximately the same for the “base” and for the “thermo” cases. However, when comparing the three economic scenarios, it is evident that the total electricity output in 2030 of the “ARIMA” scenario is approximately 60 percent greater than that for the Caaetê scenario, and that the output of the Abatiapé scenario is almost five times larger than that of the Caaetê scenario. Thus, uncertainty in economic assumptions is clearly an important factor in developing scenarios for economic growth and, in turn, for total energy consumption.

The share of electricity output by type of power generation technology used is primarily sensitive to economic assumptions, with only a secondary impact, in some cases, on the assumed constraint regarding thermal power plant share. For example, hydroelectric power plants comprise a 92 percent share of total electricity production in 2030 in the Caaetê Base Scenario, based upon 86 GW of installed capacity, and 83 percent share in the Abatiapé Base Scenario, based upon 338 GW of installed capacity.

Emissions increase by 176 percent in the Caaetê Scenario, 92 percent in the ARIMA scenario, and only 20 percent in the Abatiapé Scenario if a maximum thermal plant market share is required. These values are consistent with the relative increase in the thermal power plant share of 174 percent in the Caaetê Scenario, 91 percent in the ARIMA Scenario, and 20 percent in the Abatiapé Scenario, when compared with the respective base scenarios.

Table 7. Results of MARKAL: Base Year and Scenarios for 2030 (PJ)

Results Description	**Base Year (1995)**	**Caaetê (2030)**		**ARIMA (2030)**		**Abatiapé (2030)**	
		Base	**Thermo**	**Base**	**Thermo**	**Base**	**Thermo**
Total Electricity Output	3,576	9,932	9,933	17,115	17,115	46,471	46,472
Electricity Output by Fuel used for Power Generation							
Hydro	3,012	9,176	7,895	15,290	13,642	38,808	37,224
Thermo	519	738	2,020	1,807	3,455	7,645	9,230
Renewable	38	11	11	11	11	11	11
Nuclear	7	7	7	7	7	7	7
Useful Electricity Demand Across Economy Sectors							
Agricultural	125	375	375	688	688	2,665	2,665
Commercial	683	1,708	1,708	4,891	4,891	10,118	10,118
Industrial	1,594	3,537	3,537	5,955	5,955	20,958	20,958
Residential	646	3,132	3,132	3,438	3,438	6,216	6,216
Transport	16	30	30	51	51	173	173
Use of Renewables for Electricity Production	3,333	10,334	8,877	17,282	15,408	44,008	42,207
Total CO_2 Emissions From Burning Fossil Fuels for Power Produc. (thousand tonnes)	124,000	175,000	484,000	433,000	831,000	1,840,000	2,222,000

It seems clear that sectoral electricity use is a function of the economic assumptions, and does not depend on thermal power plant market share. The result "Use of Renewables for Electricity Production" includes the power plants using renewables as well as the hydro plants.

Figure 4. Total Electricity Output for Base Scenarios

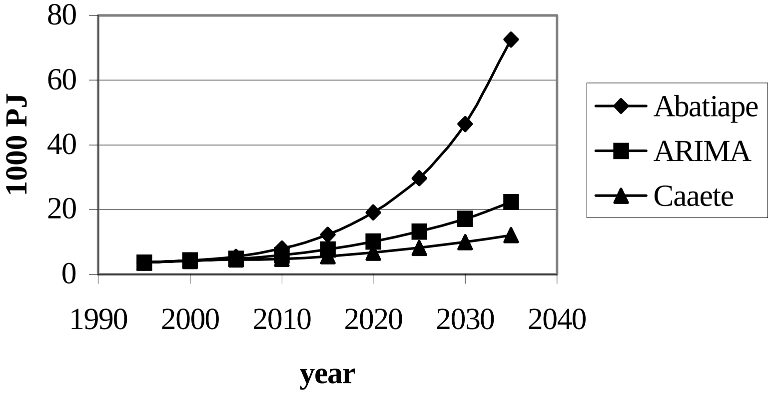


Figure 4 shows the total electricity output, for each Base Scenario, for the time frame considered. The temporal aspect of the projections can be better visualized through this graph. At 2035, the last year considered in this study, the total electricity output ranges from 12,000 PJ in the Caaetê Base Scenario to 72,000 PJ in the Abatiapaé Base Scenario.

8.0 DISCUSSION OF RESULTS

The electricity output by fuel used for power generation presents expected results. The electricity produced by renewables decreases from the base year to the future out years, and the electricity production from nuclear power plants remains constant. These two trends are independent of the scenario assumed. The reason that there is no increase in production from both of these categories is because of high initial investment costs for new capacity. In the case studies presented here, the model chooses less expensive technologies even though renewables and nuclear are options available in the range of possible technologies. The reason that the production from renewables decreases is because of retirement of older existing capacity. As Brazil has two nuclear plants, being one recently built, the model will use these plants.

To attend to the demands projected by the scenarios, the model will have to choose between hydro and thermo plants. If no constraints are imposed, there will be a dispute between the high investment cost of a hydro plant, but “zero” fuel cost, and the less expensive investment cost of a thermo plant, but high cost for fuel. When a constraint of increasing the use of thermoelectricity is imposed, the model chooses the least costly combination of thermal technologies to satisfy the constraint. In this case study, diesel technologies were chosen by the model in order to provide the least cost solution to expand the electric system. As a result, more supply of diesel oil is needed and the model’s option is to increase diesel imports.

According to Brazilian Energy Balance 1999, total hydraulic resources, including catalogued and estimated, were 143 GW at 1998. This will be enough to cover the proposed installed hydro capacity of approximately 86 and 133 GW for Caaetê and ARIMA economic scenarios, but not sufficient for Abatiapé economic scenario, supposed to require approximately 338 GW. As statistical data has shown that hydraulic potential in Brazil has increased an average of 3,300 MW per year, we could assume that total hydraulic resource at 2030 would be approximately 250 GW, still not sufficient to attend Abatiapé electricity demand. In this case, a constraint on hydroelectricity use should be included in Abatiapé economic scenario, in other to obtain another option to supply electricity demand. With respect to the proposed use of diesel technologies, there is no resource constraint since the Brazilian national agency ANP allowed companies to import higher quality petroleum products at market prices. Further greater participation of the private sector and of international investors is expected, including not only operators in the sector but also other important players such as investors, banks, supplies of equipment, engineering companies and consultants.

9.0 CONCLUSIONS

The process of getting data for MARKAL is not an easy task. Country-specific data are usually hard to obtain in developing countries, and national energy balances are not frequently available. Characteristics of resources and technologies can be taken from the many existing MARKAL databases, but the more realistic data analysts can use, the more relevant the results will be. A key contribution of this work was to compile country-specific data for Brazil for energy resource, conversion, process, and end-use technologies, and regarding economic scenarios.

The process of developing case studies is one in which new scenarios are established, through the use of constraints, defined according to the policy decision that is being tested. Decisions such as restriction on emissions are easily simulated in MARKAL, and the implications of such police on domestic production, imports and exports of resources, as well as investments in new capacity, are easily analyzed.

The results from this simple case study illustrate how competition among the many demand technologies to satisfy end-use demands, exogenously given to the model, will result in substitution among fuels. MARKAL is sensitive to the most important features of energy systems, such as the limited availability of primary sources and limitations on import and export of energy carriers.

In order to use the model in its full potentiality, the user should construct several scenarios and analyze differences as well as similarities among their MARKAL results. By varying some parameters the user will be able to measure the sensibility of the system to those variations.

The example here studied showed that the policy to increase thermal contribution to the power sector in 20 percent in 2010 does not affect electricity end-use demands. However, the decision to use diesel power plants with a consequent increase in diesel imports, as the best option suggested by the model, requires economic and political considerations.

This methodology should be able to provide Brazilian decision-makers with insights to make decisions on the proposals for the expansion of the electric power systems of the concession holders. It will also be helpful to government bodies for the actual implementation of the projects.

The use of an energy system optimization model, such as the stand-alone MARKAL mode, to perform prospective analysis of long term energy balances under different scenarios, will provide international credibility of results, the possibility of direct result comparison with other countries, and the possibility of participating in calculations of the benefits of joint international implementation of CO_2 emission reductions.

10.0 FUTURE WORK

In order to account uncertainties associated with technology characteristics, emissions and cost, other case studies will be performed, such as: (1) a CO_2 constraint for power production, in which CO_2 emission intensity of the economy (CO_2/GDP) should not exceed the 1996 rate of 126 thousand tons of C/US$ million; (2) expansion of the power production system based exclusively on renewable technologies; (3) analysis of the power production system under different world oil price projections; and (4) analysis of the power production system under different values of conversion technology efficiencies.

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