

# Nuclear energy over a 30-year scenario

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## Introduction

An analysis of the future of nuclear energy over a 30-year time frame must comprise at least the following aspects: electricity demand and the comparative environmental, technological and strategic costs (including national reserves and non-proliferation).

The comprehensive nature of these aspects requires a concise treatment and referral to previous works, as it is done here.

## Electricity Demand

In Brazil, within our time frame, the justifiable peaceful application of a nuclear program is the generation of electrical energy. The share of nuclear-generated electricity depends on the country's energy requirements, which, in turn, are a function of economic growth and the available alternatives.

The ill-conceived estimates of economic growth were the weak link in energy planning from the 1970's to the 1990's. Successive overestimates of economic growth and of the corresponding demand for electrical energy led to a general disbelief regarding the threat of shortages in the supply of electricity. This was one of the causes of the laxness of energy plans, which caused the undersupply that led to the extensive blackout of 2001.

These difficulties motivated the members of the OSCIP e&e team (Public Interest Civil Social Organization – Economy & Energy) to study the restraints on Brazilian growth and identify the chief limitation: the reduction of capital productivity in the 1970's and 1980's that curbed the country's future growth. These difficulties have only increased since 1994 due to the high interest rates applied to control inflation. The result was a decrease in the rate of internal savings that was not offset by the entry of foreign savings, as was expected. The net result of the loss of capital productivity was a plummeting investment rate and the inability to generate the desired economic growth.

Energy planning, practically abandoned in the 1990's, was resumed in President Lula's first mandate with basic premises of growth below what the government desired. The 2030 Plan assumed that the GDP would grow by 4% per year (2005-2025), or the equivalent of 3.2% GDP growth *per capita*.

We will examine here three assessments of electricity demand, all of them with basically coincidental GDP projections: e&e (Alvim et al, 2007), EPE (Empresa de Pesquisa Energética) in “National 2020 Plan: Supply Expansion Strategy”, and the results of the “Agenda Elétrica Brasileira” published under the auspices of WWF-Brasil (Worldwide Fund for Nature) – Sustainable Electricity Agenda 2020.

Our methodology and the results we obtained are described below.

### *Methodology and comparison of results*

The methodology used by e&e to project energy requirement is analogous to the one that, quite successfully, has been predicting Brazilian growth over the last ten years. Its general traits are:

- 1 Studying energy and economic variables (and their relationship) with stable and predictable behavior over their time frame, determining the best arrangement to describe the future by means of curves that usually stabilize at their maximum value.
- 2 Using data from more developed countries and from Brazilian hydraulic potential to choose the reference and saturation values, whenever applicable.
- 3 Seeking of best adjustment between the country’s historical data and the adopted reference value.

It should be noted that simply applying the best adjustment in (1) would generate deterministic values. However, the aim of this methodology and of the corresponding computer program is, on the contrary, to achieve consensus regarding the more probable scenario without the rigidity of pre-established relationships. The GDP used in the projections comes from applying the *projetar\_e* semi-empirical macroeconomic model, the results of which are automatically reflected in the demand of energy.

The GDP is then correlated with the demand for equivalent energy, whereby the energy efficiency in each sector is used to determine the equivalence with a reference fuel of choice. The energy projection is based on the equivalent energy/GDP ratio, which has shown predictable behavior over the 35 years for which there are data available in the Balanço Energético e das Contas Nacionais (Energy Balance and National Accounts).<sup>a</sup> As shown in Figure 1, this ratio has slowly increased over the years, but reveals a tendency to saturate over time.

The best adjustment of past data projects 0.513 koe [kilogram of oil equivalent]/dollar (2003) for 2030, whereas the value actually adopted leads to 0.491 koe/dollar (2003) – or 4.3% lower. It should be noted that the program limits the adjustment freedom by comparing the projection with historical behavior and by suggesting limits defined by other countries’

experience. As a result, the values established by the consensus groups usually do not diverge much from the historical trend.

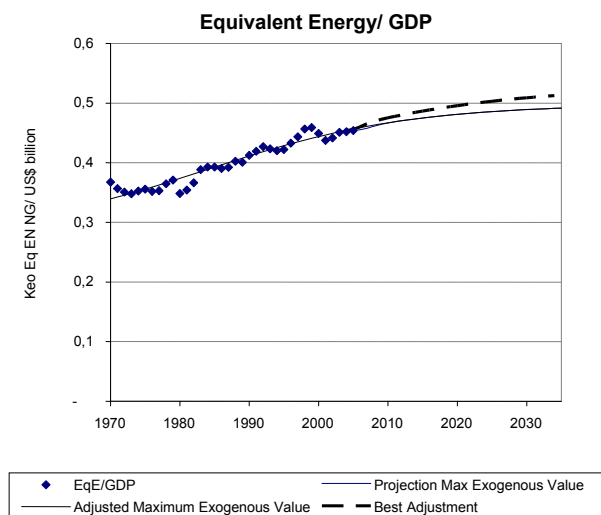


Figure 1. Illustration of the methodology used to project demand in equivalent energy as a function of GDP (in 2003 US dollars), both under the best adjustment hypothesis and by imposing the limit of (countries with) less energy-intensive countries (Western European countries and Japan).

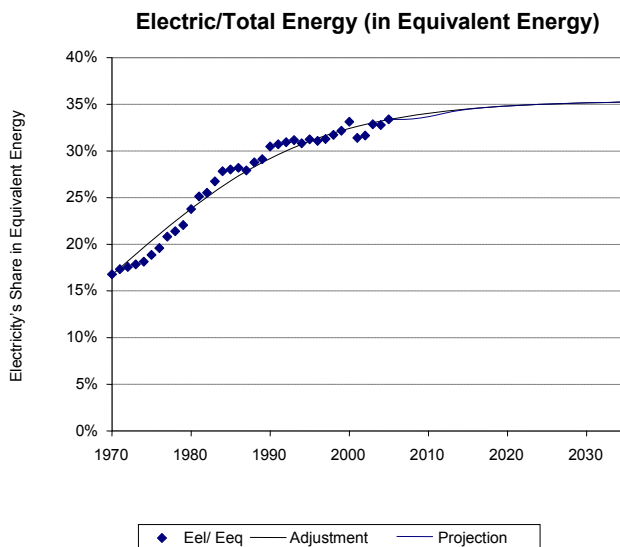


Figure 2. Share of electric energy in equivalent energy.

The program then projects the share of electric energy in the total (expressed in equivalent energy). The result is shown in Figure 2.

One inconvenience of working only with the best adjustment is that circumstances (such as the 2001 blackout) can alter the short-, and sometimes middle-range trends, and change the best adjustment by introducing new years in the series. Figure 2 shows a case in which, after a moment of transition around 2000, the behavior of the curve almost returned to the previous value.

If we adopt the GDP growth hypothesis previously mentioned, this methodology results in the e&e projections shown in Table 1, which also includes the results from EPE and WWF, and a revision of the e&e study that assumes the electric energy/GDP ratio will evolve consistently with the conservation of energy hypotheses adopted by EPE.

Table 1. Comparison of results: e&e (original and revised), EPE and WWF.

		2000	2005	2010	2015	2020	2025	2030	2035
GDP e&e	(2000=100)	100	111	129	158	200	256	335	444
GDP ePe	(2000=100)	100	111	137	168	195	239	303	
Electric e&e <sup>a</sup>	TWh	332	375	451	576	743	966	1,280	1,710
Electric e&e <sup>r</sup>	TWh	332	375	441	544	695	900	1,188	1,582
Electric EPE	TWh	321	388	471	575	703	859	1,046	
Electric WWF	TWh		388			500			
<b>Growth rates</b>		<b>2000</b>	<b>2005</b>	<b>2010</b>	<b>2015</b>	<b>2020</b>	<b>2025</b>	<b>2005</b>	<b>2005</b>
		<b>2005</b>	<b>2010</b>	<b>2015</b>	<b>2020</b>	<b>2025</b>	<b>2030</b>	<b>2020</b>	<b>2030</b>
GDP e&e	% year	2.2%	3.0%	4.2%	4.7%	5.1%	5.6%	4.0%	4.5%
GDP EPE	% year	2.2%	4.2%	4.2%	3.0%	4.2%	4.9%	3.8%	4.1%
Electric e&e <sup>a</sup>	% year	2.5%	3.7%	5.0%	5.2%	5.4%	5.8%	4.7%	5.0%
Electric e&e <sup>r</sup>	% year	2.5%	3.3%	4.3%	5.0%	5.3%	5.7%	4.2%	4.7%
Electric EPE	% year	3.8%	4.0%	4.1%	4.1%	4.1%	4.0%	4.0%	
Electric WWF	% year							1.7%	

e&e<sup>a</sup> = original values; e&e<sup>r</sup> = revised values; \* TWh = terawatts/hour

A supplementary way to test the consistency of projections is to study the energy intensity per GDP unit as a ratio of GDP per capita in Purchasing Power Parity (PPP). The United States' EIA/DOE (Energy Information Administration/Department of Energy) Web site contains data on energy intensity for the consumption of primary and electric energy for practically every country or geographical unit. The adjustment comprises the approximately 200 countries and geographical units registered at the United Nations and shows strong correlation. When the whole is limited to countries with population over 10 million, the adjustment is improved, as can be seen in Figure 3. The slope of the line of adjustment remains practically the same.

It should be noted that, for each country, the energy/inhabitant and GDP/inhabitant curves are only representations (on a different scale)

of the energy x GDP curve. However, by representing several countries, it is possible to compare data from countries in different stages of economic growth and take into account the economic growth of each one.

### Electricity and GDP (PPP) per capita in 2004

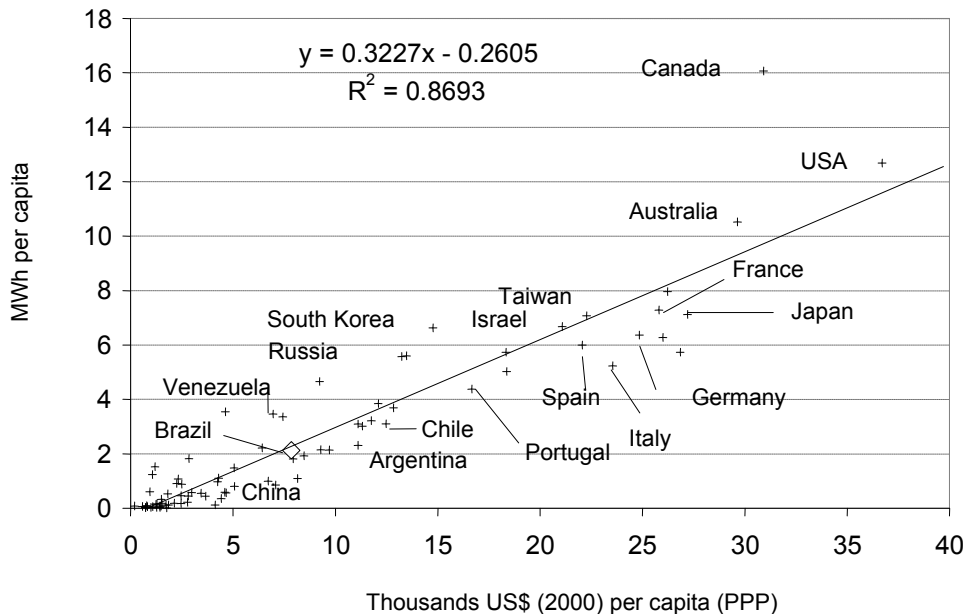


Figure 3. Electric energy/GDP for countries with population over 10 million. (Some countries indicated.)

With the variation of the GDP/inhabitant ratio, the behavior of the energy/inhabitant ratio can also be observed for individual countries or groups of countries. There were no significant variations for groups of countries between 1990 and 2004. The dynamic behavior of the two variables of intensity surveyed (electricity per GDP and per inhabitant) can be drawn on a graph, where the projected data are also represented.<sup>b</sup> Extrapolated for Brazil, the numbers would continue below the world trend for 2004 (which coincides with that of 1990).<sup>c</sup> Figure 4 shows two GDP scales: actual (in 2000 dollars) and in purchasing power parity<sup>d</sup>.

Figure 5 shows the ratio of electricity consumption/GDP (PPP) per GDP/inhabitant according to the projections of E&E, EPE and WWF.

The results of the survey sponsored by WWF, which included the participation of many respected entities involved in energy conservation or alternative energies, are incongruous with those of the other two studies, and there was some public controversy between its authors and those of the EPE survey.

**Electricity Consumption and GDP (PPP) per capita in Brazil  
Compared with Adjusted Value for 198 Countries**

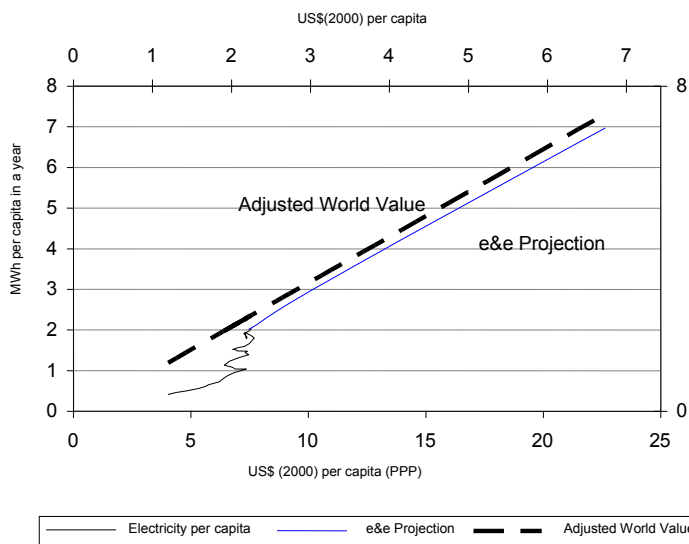


Figure 4. Evolution of the electric energy/inhabitant and GDP/inhabitant ratios according to the e&e projections. The numbers corresponding to the real GDP in 2000 dollars are only approximations.

**Electricity Consumption and GDP (PPP) per capita in Brazil  
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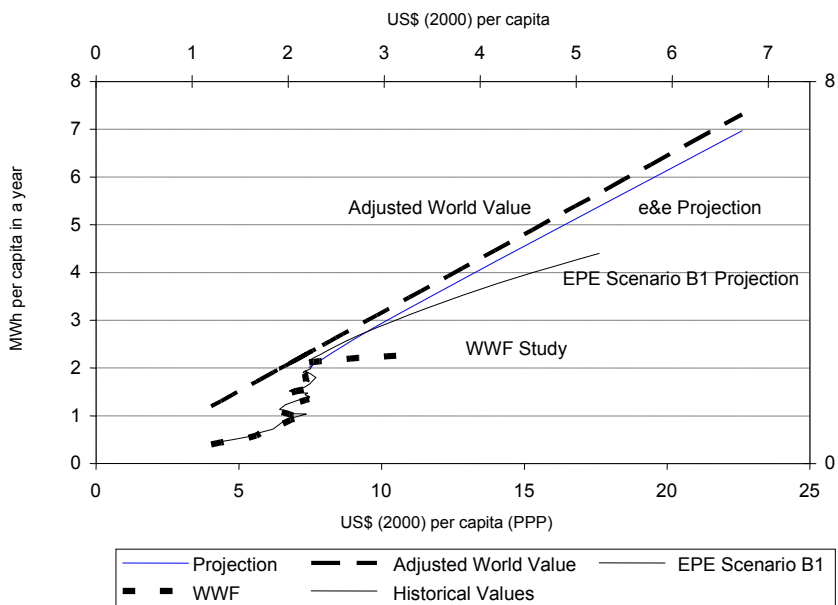


Figure 5. Projections of the ratio electricity/inhabitant compared with world trends.

It should be noted that the time frame of each projection is different: e&e's is 2035, EPE's is 2030 and WWF's is 2020. The e&e's projection begins below the current world standard and gradually departs from it; EPE's departs somewhat more from this standard, while WWF's completely diverges from it, assuming strong GDP/inhabitant growth while maintaining *per capita* consumption of electricity almost constant.

Figure 6 is interesting, as it compares the behavior of the variable electricity consumption/GDP projected by the aforementioned studies.

This comparison reveals that EPE's projection essentially maintains the ratio electricity/GDP of the last years of the series, whereas e&e's admits the continuation of a moderate increase in the intensity of electricity usage and a tendency toward saturation after 2035. WWF's value for 2020 is 14% lower than the same value in the 2001 blackout.

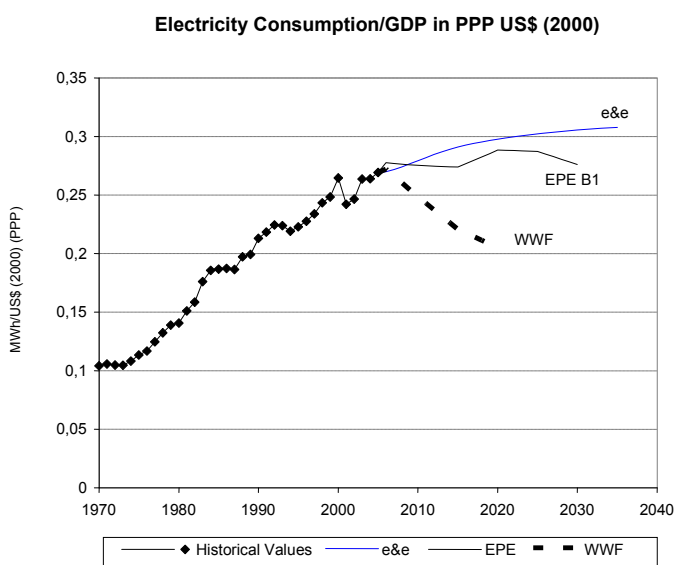


Figure 6: Electricity consumption/GDP in the three studies.

It should be noted that, over the last 40 years, Brazil has become accustomed to admitting that electricity consumption would grow more than the GDP. The most likely trajectory for this ratio is to tend towards becoming a constant value in the period under consideration.<sup>e</sup> The current world trend is a very slow decrease of this ratio, as can be seen in Figure 7, which uses data from EIA/DOE to show the evolution of electrical intensity in the economies of various regions of the world.

Figure 7 shows a slow convergence of the various regions toward the same average value. Electricity intensity in North America and Eurasia is falling, while in South and Central America (including Brazil) it is increasing. The Middle East has exceeded the world average and does not conform to the expected convergence. Africa, Asia and Oceania

**Electric Energy/GDP (PPP) in US\$ (2000)**

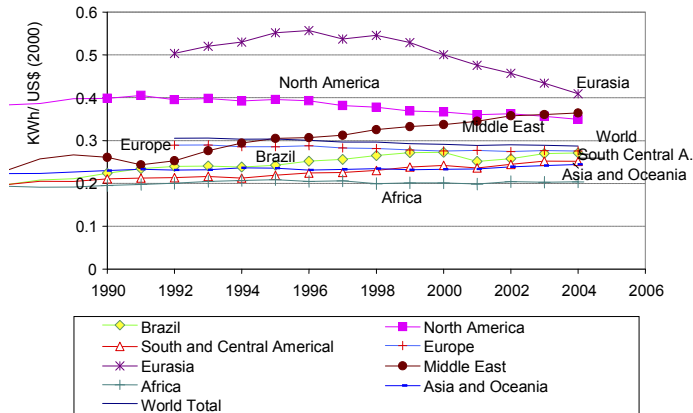


Figure 7. Electricity/GDP for several regions. The ratio for Brazil remains practically constant throughout the period, while the world's shows a slight decrease.

have maintained their intensity, while Europe's fell slightly, following the world average. This behavior reinforces the hypothesis that energy intensity tends to remain approximately constant over the next years.<sup>f</sup>

It must also be noted that worldwide solutions for the scarcity of liquid fuels rely basically on electric energy. This could refuel demand for electricity.

Assuming economic growth of 4% a year, the demand for electrical energy in 2035 should be between 1,600 and 1,700 TWh (terawatt/hour): it is upon this demand outlook that we will analyze the role of nuclear energy.

### Comparative costs of electric energy generation

Several studies of comparative costs were carried out around the world after the recent oil crisis and in view of the greenhouse effect. (Arguably,) The most significant is possibly the International Energy Agency's (IEA) Projected Costs of Generating Electricity – 2005 Update. The methodology employed in our assessment is a simplification of the one adopted in that study that enables us to easily evaluate changes in costs.

In conventional thermal power plants, fuel is the main cost component in generating electricity, whereas in nuclear plants most costs are fixed. But when we consider expanding production (or replacing deactivated plants), the comparative costs of production in the plants to be built are of greater interest. IEA's study considered actual plants that were recently built.



To the assayed results (of typical power plants) were added the corresponding costs of CO<sub>2</sub> emissions (which are still not taken into account commercially in the United States, as the country has not ratified the Kyoto protocol). Several measures to capture carbon emissions are being studied in the United States and, undoubtedly, this will become an important parameter in choosing fuels for generating electricity over the next years. Current estimates of the costs to capture CO<sub>2</sub> emissions are higher than the cost of coal, US\$ 100 per metric ton. The value of US\$ 30 per metric ton of CO<sub>2</sub> is used merely as an illustration: it corresponds to the assessed cost for purchasing carbon credits in the terms of said Protocol and is the minimum amount currently under consideration. Table 2 shows the comparative costs for the various sources of electricity generation.

Table 2. Comparative costs of electricity generation in the United States.

Entry data	Symbol	Unit	Oil	Natural gas	Coal	Nuclear	Diesel
Life span	T	Year	25	40	40	40	20
Construction & installation time	T	Year	3	3	4	6	2
Investment	I	US\$/kW (kilowatt)	1340	609	1366	1894	19000
Decommissioning cost	CD	US\$/kW	0	0	0	269	0
Average capacity	FCM	Non-dimensional	0.8	0.8	0.8	0.8	0.8
Interest rate	J	Year <sup>-1</sup>	10%	10%	10%	10%	10%
Decommissioning fund return rate	R	Year <sup>-1</sup>	0	0	0	2%	0
Conversion efficiency	H	Non-dimensional	0.41	0.54	9.46	0.33	0.4
Fuel price	PC	US\$/MWh <sub>th</sub>	25.67	24.44	4.98	1.35	28.24
Annual operations and maintenance cost	CAOM	US\$/kW.a	26	26	50	63	26
Emission of CO <sub>2</sub> for US\$/tCO <sub>2</sub> emitted	30	tCO <sub>2</sub> /MWh	0.276	0.200	0.337	0.000	0.264
Cost per MWh (megawatt/hour)							
Cost of carbon emitted	CCE	US\$/MWh <sub>el</sub>	20.2	11.1	22.0	0.0	19.8
Fixed generation cost	CFG	US\$/MWh <sub>el</sub>	26.9	13.5	30.2	45.0	21.3
Cost of fuel	CC	US\$/MWh <sub>el</sub>	62.6	45.3	10.8	4.1	70.6
Total cost of generation	CTG	US\$/MWh <sub>el</sub>	89.6	58.8	41.1	49.1	91.9
Total cost with CO <sub>2</sub> emissions	CT	US\$/MWh <sub>el</sub>	109.7	69.9	63.0	49.1	111.7

The results are also shown in Figure 8, where fixed costs (including operational and maintenance costs) can be compared to fuel costs. The above mentioned cost of CO<sub>2</sub> emissions is also represented.

According to the premises of this comparison, the cost of nuclear generation is competitive with the cost of generation from oil and natural gas, even if coal-generated electricity (predominant in the US) remains cheaper than nuclear. But the nuclear option becomes economically competitive when we take into account even modest costs to suppress CO<sub>2</sub> emission. The cost analysis shown here can be taken as an approximation of the current European situation. It should be noted that the deactivation of most coal-based power plants in Western Europe was due to other environmental reasons that preceded concern about greenhouse effects – and, in countries such as the UK, it was also due to labor issues.

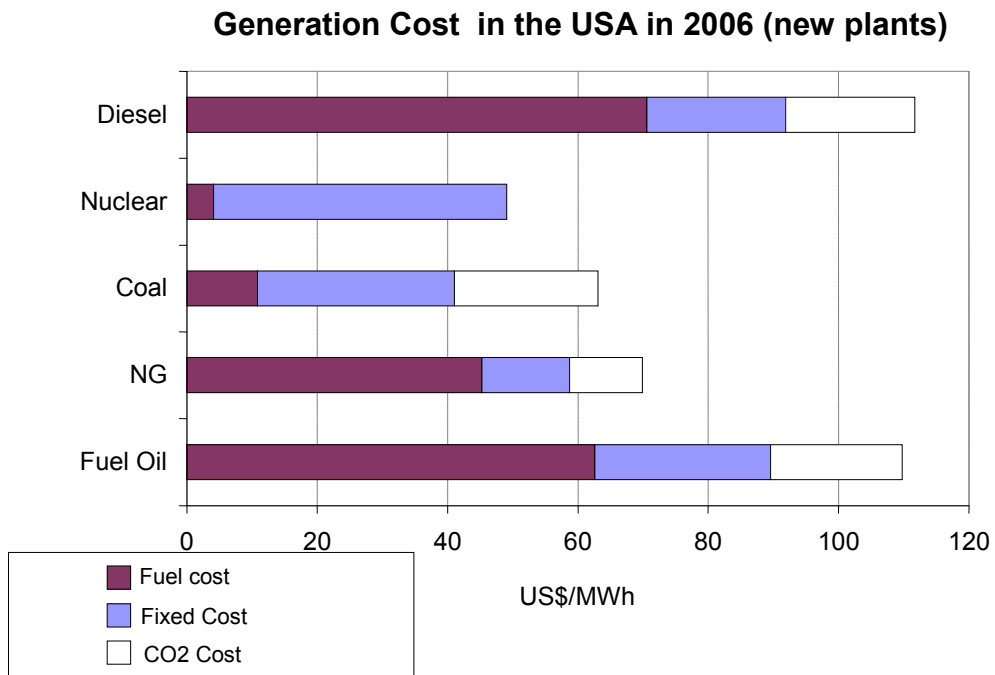


Figure 8. Comparative costs of generating electricity in new power plants and current fuel prices in the US (2005).

A similar analysis is being undertaken for Brazil, with the peculiarity that most of the country's electricity comes from hydroelectric plants. Thermal plants that are built will necessarily have a regulating role, seeing that the reservoirs that supply the hydroelectric system are slowly dwindling (Alvim *et al*, 2005). Different average capacity factors are expected for thermal plants; in 2005, for instance, the capacity factor of conventional

thermal plants was 31%; if we exclude plants from the isolated system, the capacity factor was only 21%.

Nuclear and coal plants should be aimed at complementing the thermal plants with the larger capacity factor, because they are plants with predominantly fixed costs. Other plants will complement the Brazilian generation grid with lower capacity factor. Brazil has considerable potential for generating electricity from biomass, particularly sugarcane bagasse. This energy source is available during the dry season, when there is a water deficit in plants with no adequate reservoir.

In a preliminary analysis, hydroelectric energy is still advantageous in terms of generation costs. However, environmental deadlocks prevent this potential from being fully utilized. On the other hand, future demand will be concentrated in the southeast and northeast of the country, where the hydroelectric potential (if it were fully exploited) would soon be exhausted.

The largest power plants are being planned for the Amazon region, where environmental difficulties are even greater. But it seems probable that, because of its economic advantages, considerable hydroelectric generation capacity will be installed in that region. The plants of Belo Monte and Rio Madeira were included in the PAC – Growth Acceleration Plan. In order to make the projects acceptable to society, the flooded areas (and the reservoirs) were considerably reduced in both projects. In the case of Rio Madeira, there was the additional need to prevent the reservoir from overflowing into Bolivian territory, which would considerably increase the complexity of the undertaking.

That is, even if the estimated generation costs are lower, the environmental and financial uncertainties do not allow us to expect installed hydroelectric capacity to be more than 180 GW (gigawatts) in 2035, out of an estimated total of 260 GW. That is the threshold of our upper estimate, including the projections of the 2030 Plan, as shown in Figure 9.

The threshold does not take into account the evolution of the cost of generating energy. Figure 10 shows two estimates of the evolution of the cost per MWh from Brazilian hydroelectric power plants – which, although quite different, coincide at the economic threshold of approximately 150 GW of installed capacity, where the cost of hydroelectric energy would exceed US\$ 55 /MWh.

Considering a 12% rate of technical losses, the 150 GW limit corresponds to approximately 720 TWh of generated energy, or a final consumption of 640 TW/h. In other words, if global demand in 2035 lies between 1,600 and 1,700 TWh, approximately 1,000 TWh will have to be thermal. Thermal plants would no longer have the supplementary role they have today and we may assume that the average capacity factor will have increased. If it reaches 70%, the installed thermal potential would be

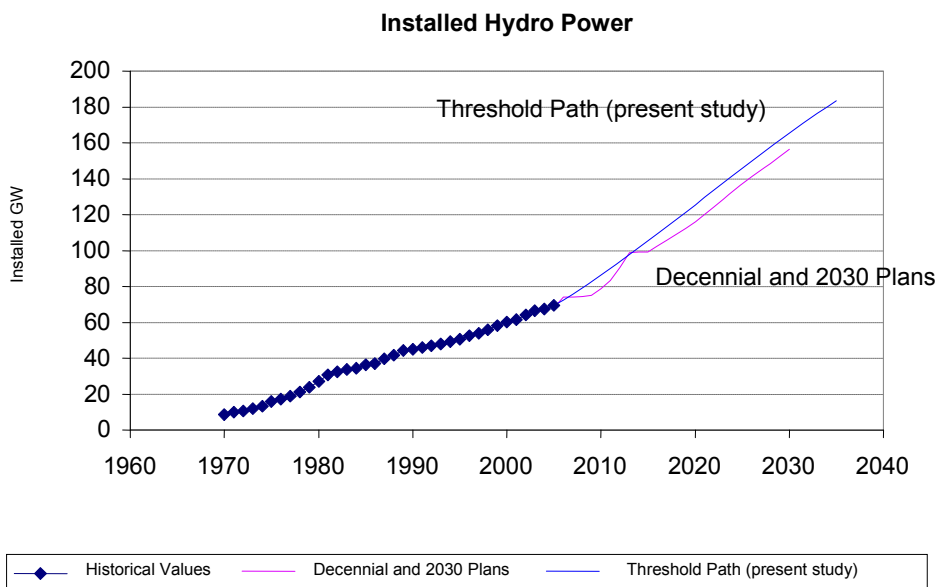


Figure 9. Installed hydroelectric power in the reference scenarios of the 2025 and 2030 plans, and the threshold considered in this essay.

approximately 170 GW; if we assume that 30% of this potential is nuclear, this would correspond to a capability of 52 GW, or approximately forty Angra 3-type reactors.

In the official planning (2030 Plan), nuclear generation capability will reach 7.2 GW in 2030, comprising four additional 1 GW units besides Angra 3. If we extrapolate the 2030 Plan for another five years, we reach a total of 10 GW generated by nuclear plants in 2035.

The main problem in the 2030 Plan seems to be related to the demand of natural gas, which would reach 26 billion m<sup>3</sup> per year in that year, corresponding to approximately 6% of current Brazilian reserves (including inferred reserves). Since the generation of electricity is only one of the uses of natural gas (approximately 20% both in the US and in Brazil), consumption of natural gas in 2030 would correspond to almost 30% of current reserves in only one year. Brazil holds only 0.2% of the known world reserves of natural gas and only 0.9% of oil reserves (BP Statistical Review of World Energy, June 2005). In other words, the option of producing electricity from natural gas implies importing gas from neighboring countries (South and Central America hold 8.5% of the world reserves). This problem will be discussed below in the strategic analysis.

In Brazil, the cost of generating electricity from natural gas is lower than from nuclear sources. In 2005, the average price of natural gas per

ton of oil equivalent was half that of oil (BEN/MME – Balanço Energético Nacional/ Ministério de Minas e Energia, 2006). One would expect it to cost somewhat more than fuel oil, considering the superior characteristics (including environmental ones) of natural gas.

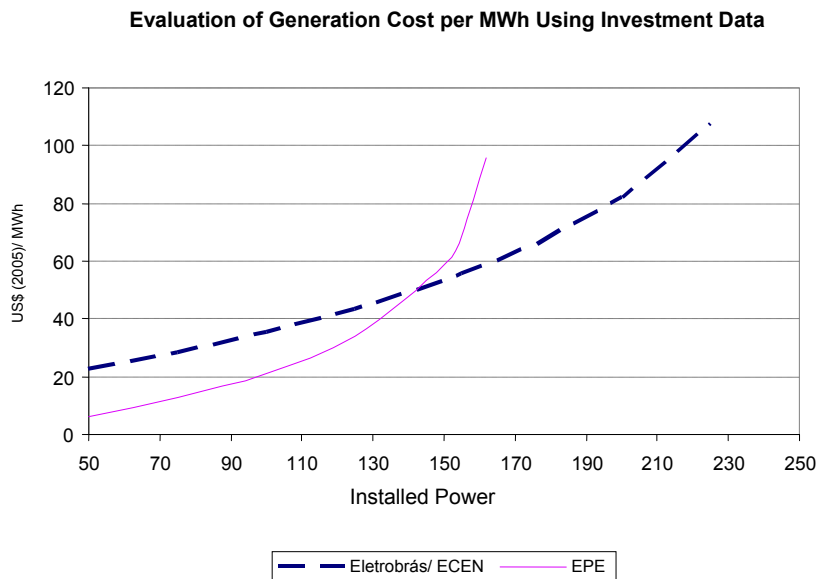


Figure 10. Assessment of the cost of energy based on updated Eletrobras and EPE investment data for socially and environmentally viable plants. Generation costs calculated by the authors.

From an analysis of nuclear generation costs in the US, we can infer that nuclear sources tend to be competitive with natural gas if oil prices (which are a reference for gas prices) remain above US\$ 40 per barrel. Inasmuch as Brazilian prices are on a par with international ones, the domestic outlook should also reflect the international one.

From a costs perspective, and if the aforementioned hypotheses of price evolution hold, nuclear sources tend to be competitive with other commercial sources in the time frame of our study.

### **Environmental concerns**

Environmental objections to nuclear energy have lately become less intense. We may say that, in part, they were negatively offset by greater concerns with proliferation, which will be dealt with later.

The main reason for the attenuation of opposition to nuclear energy relates to the perception that the issue of long-lasting waste is not restricted to nuclear plants; it also involves thermal plants if we compute the emission

of greenhouse gases. There are no direct emissions of such gases in nuclear plants.

In order to have an idea of the mass and volume of the residues from both a nuclear and a conventional thermal plant, consider the following. A 1.3 GW nuclear plant (at 80% capacity) requires the replenishment of 54 tons of fuel (enriched uranium) per year, equivalent to one third of its total load, which amounts to a volume of 50 m<sup>3</sup>. The generation of the same amount of electricity (approximately 9 TWh) would produce from 2 to 3 million tons of CO<sub>2</sub> per year (in a natural gas or coal plant), releasing a volume of 1 to 1.5 billion m<sup>3</sup> of this gas into the atmosphere. In other words, there is a 1:50,000 ratio between the mass of residues from a nuclear and a thermal power plant.

The environmental risks of nuclear energy can be divided in four categories:

- 1 Risks from normal plant operation.
- 2 Risks from accidents.
- 3 Risks in the fuel cycle (production chain, from mine to fuel).
- 4 Risks in the accumulated wastes.

Firstly, normal operation of the nuclear Pressurized Water Reactor (PWR) plants adopted by Brazil (current and future plants) can be considered relatively clean in comparison with other types of thermal generation plants, and there are no significant objections to operating plants from local populations in Brazil and abroad.

The main worry of neighboring populations and of environmental analyses are the possible accidents from reactor failure and, ultimately, from terrorist action.

Regarding the PWRs, no accidents with significant environmental damage have ever recorded. The most serious incident, at Three Mile Island, had no direct environmental consequences, yet led to the improvement of current reactors and to the considerable changes that are being incorporated into the next generation of reactors. The current perspective (International Energy Outlook 2006) is that, worldwide, there will be a 31% increase in nuclear energy generation between 2003 and 2030, and that the forecast number can be exceeded in case of higher fuel prices and greater implementation of the Kyoto Protocol.

The greatest probability of contamination risk lies in the fuel cycle, especially critical accidents such as the one that occurred in the fuel plant of Tokaymura, Japan, in 1999. These accidents are more common in military plants or in those that require much greater enrichment than the PWRs, and usually result from breaches in safety procedures. Normally, they are very short-duration accidents (thermal expansion usually halts

the reaction), that affect the direct operators. The Tokaymura accident, which lasted several hours, was an exception. The site near the plant was affected by radiation (gamma rays and neutrons), but external contamination was not serious. An accident of much graver consequences might come from the accidental or intentional dispersion of plutonium from reprocessing plants. These two types of accidents are highly unlikely in Brazil, as the level of enrichment used here in commercial plants is relatively low (4%) and there are no plans for domestic fuel reprocessing in the next decades.

It should be noted that, as in any type of activity, such accidents must be compared to accidents in other fuel cycles, including coal mine collapses, fires in oil installations and hazardous transportation of liquid and gaseous fuels.

In Brazil, the type of radiation dispersion of gravest concern relates to mining activities (not necessarily related to the nuclear cycle), where effluents can disseminate natural radioactivity found in ores, facilitated by the chemical attack used to extract uranium and other materials.

In addition to insufficient financial and human resources for licensing and inspecting activities, Brazil's nuclear regulatory agency, CNEN (National Nuclear Energy Commission), faces the peculiar problem of incompatible interests, being also responsible for managing the country's nuclear industries [INB – Indústrias Nucleares Brasileiras]. This anomaly, acknowledged by CNEN's current directors, persists in spite of numerous national and international recommendations against it.

Regarding low- and medium-activity waste currently stored *in situ* at the Angra plant, a definite solution must be reached before expansion of the Nuclear Program. The solution to this problem poses no technological difficulties; rather, it is a matter of political will and public acceptance.

There is, however, the greater problem of finding a definite repository for medium- and high-activity waste (essentially, irradiated fuels), the technical solution for which seems to be underground deposition at a place with proper geological conditions that, nevertheless, reserves for future (and current) generations the possibility of an eventual intervention. This is probably the strategy that will be implemented in the Yucca Mountain repository in the United States.

It is impossible to overstress that a definite repository for nuclear waste must be capable of containing radioactive residue for many thousands of years. This is a problem with which humanity has no experience (the time frame is longer than that of so-called civilized human activity) and whose solution depends on past geological behavior.

Regarding this point, the line of reactors adopted by Brazil and

predominantly by the world generates a lower volume of solid waste than its closest competitor, the natural/heavy water uranium reactors – PHWRs (Pressurized Heavy Water Reactors). Reprocessing these fuels by reusing the plutonium through irradiation of mixed oxides (plutonium and uranium) is something that is already being done in several developed countries, considerably reducing the volume of high-activity residue to be stored (products that result from the fission of the uranium nucleus<sup>g</sup> and from residual plutonium). In Brazil, no decision was made to follow the reprocessing road, which leads us to believe that fuel storage will be carried out with no changes in their physical or chemical state.

Therefore, we may say that there is still no solution for nuclear waste (solid, small volume and highly toxic for thousands of years) and for the residues of other thermal plants (gaseous, high volume and lasting hundreds of years). In Brazil, more attention should be given to radioactive dispersion in mining activities. Another pressing need is to dissociate the CNEN from the industrial activities of the fuel cycle.

### **Technological Aspects**

Brazil is one of the few countries that masters the nuclear fuel cycle – which includes mining, concentrating and purifying uranium as  $U_3O_8$  (triuranium octaoxide – yellowcake), converting it into hexafluoride, enriching it, reconvert it into an oxide ( $UO_2$  – uranium dioxide), manufacturing pellets and assembling the fuel rods. No commercial units exist for the conversion stage, and due to the enrichment capacity of the unit being built at INB (already in partial operation) most of the uranium is enriched abroad.

The development of the fuel cycle technology, promoted largely at the Navy and CNEN installations (with the support of several industrial units of the Brazilian production system) has already had considerable technological impact on domestic industries.

There are increasing restrictions in the world against the transfer of technologies directly related to the nuclear cycle and of those said to be dual-use. The availability of such technologies has to be attained domestically until the doors for their importation are opened. Considering that many of these technologies are dual-use, an eventual refusal to develop the nuclear area would lead the country to abandon several high-profit areas of the industrial sector.

In the practical experience of nations, access to these technologies is not obtained by renouncing nuclear activities (as the more developed countries wish us to believe), but by acquiring domestic capability and, to a lesser degree, by the transparency of the national nuclear program.

The country is capable of manufacturing the heavy elements of the



nuclear reactor and of the heat exchangers. However, most of the control elements are still imported. If electricity generation<sup>h</sup> is divided into smaller turbines, domestic manufacturing of these components may become possible over the next decades. The design of the next nuclear plants will still come from abroad, albeit with an increasing degree of nationalization.

Manufacturing of reactor components requires important technological expertise in the areas of materials and mechanical and civil engineering. Building a reactor enhances the expertise in managing and applying quality assurance procedures.

The technological development associated with the nuclear sector also brings important advances for the country in certain specific areas. There are growing access restrictions to these technologies that hamper development in other areas. Access to these technologies is obtained through the domestic mastery that emerges from needs created in the nuclear area.

### Strategic Aspects

Strategically, two points should be stressed: the first relates to the availability of national energy reserves and the perspective of energy dependency; the second involves the policy of non-proliferation of nuclear weapons and related technologies.

With regard to the first point, Brazilian energy reserves and resources are published annually in the National Energy Balanço (BEM) by EPE/MME, as summarized in Table 3 for 2005, including the reserve/production (r/p) and reserve/consumption (r/c) ratios.

Table 3. Reserves measured/indicated in absolute values and related to production and consumption in 2005.

	Reserves	Production	Consumption <sup>(1)</sup>	R/P	R/C	Consumption <sup>(2)</sup> in the generation of electricity
	10 <sup>6</sup> tep	10 <sup>6</sup> toe/year	10 <sup>6</sup> toe/year	Years	Years	
Oil	1668	84.3	87.7	20	19	3%
Natural gas <sup>(3)</sup>	304	14.8	22.7	21	13	18%
Coal <sup>(4)</sup>	2,756	2.3	2.3	1,174	1,204	83%
Nuclear energy	1,236	1.3	2.5	944	498	100%

Source: BEN/EPE/MME Reserves on 12/31/2005 measured/indicated considering waste in mining and processing (in the case of coal and uranium).

(1) Includes transformation.

(2) In the case of oil, electricity generation from oil products.

(3) The production of natural gas excludes re-injection; consumption includes waste.

(4) Considered as steam coal.

Table 4. Electricity generation from existing Brazilian reserves.

	Measured/ indicated reserves	For use in generating electricity	Reserves usable in generation	Efficiency in generating electricity	Generation: measured/ indicated reserves		Generation including inferred/ estimated reserves
					10 <sup>6</sup> tep	TWh	
Oil	1,668	5%	83	0.38	32	368	505
Natural gas	304	30%	91	0.41	37	435	645
Coal	2,756	85%	2,343	0.29	679	7,900	25303
Nuclear energy	1,236	100%	1,236	0.34	420	4,888	8519

Among the non-renewable fuels, coal is the one with the greatest reserves and the largest reserve/production and reserve/consumption ratios. These ratios were obtained from the consumption of steam coal and do not include metallurgical coal (for which Brazil is almost completely dependent on imports – 10.4 million tons of oil equivalents in 2005). Nuclear energy – uranium – comes next, even if we adopt the criteria of non-utilization of the residual energies of uranium and plutonium in the irradiated fuels. As for natural gas, not only is Brazil already dependent on foreign supply, but this is the non-renewable energy source with the lowest reserve/consumption ratio. The generation of thermal electricity using preferentially natural gas, as predicted in the 2030 Plan, will probably continue to be carried out with gas imported from our neighbors.

Table 4 shows the possible generation of electric energy from the reserves shown on the previous table. The last column indicates total reserves, including both inferred and estimated values. This table attempts to discriminate the part of the reserves that would be destined to electrical generation by fixing tentative limits on the use of each source based on the percentage of use in 2005 (an increase in the share of natural gas used in generation was assumed).

From Table 4 we can infer that generating electricity from coal and nuclear sources provide greater energy independence among non-renewable fuels. However, Brazilian coal, containing a large volume of ashes, is only useful for generation at the mine head, and therefore is restricted to plants in the southern region of the country. Furthermore, when we include inferred and estimated reserves, it becomes evident that the 2020 Plan's option for thermal generation from natural gas is a strategic choice to make use of the natural resources of our neighbors, with whom Brazil has a privileged relationship *vis-à-vis* other countries with a demand for natural gas. The table takes into account that there are other uses for natural gas and that it should preferably be used to co-generate electricity and heat, and not exclusively for generating electricity.

An analysis of the reserves makes it clear that steam coal and nuclear sources are important generation options. The table does not include renewable reserves, but the production of electricity from biomass will become increasingly important, particularly that derived from sugarcane bagasse.

Under the hypothesis that nuclear energy's share in 2035 would be an installed capacity of 52 GW, nuclear generation would be approximately 350 TWh (with a capacity factor of approximately 80%), and the total reserves would allow it to be maintained for 23 years. In the most probable scenario, with an installed capacity of 10 GW and the generation of 70 TWh, estimated reserves would last 110 years.

As to the second point of this strategic analysis, we must take into account that the issue of nuclear proliferation has changed significantly over the last years:

- India and Pakistan have declared and demonstrated their ability to explode nuclear military artifacts.
- North Korea has conceded that its nuclear activities are for military uses.
- Iran has had its allegedly peaceful nuclear program contested.
- The risk of proliferation of nuclear and other weapons of mass destruction was used by the United States and Great Britain as a pretext for the invasion of Iraq, in spite of the negative results of UN inspections.
- The great nuclear powers have not only practically abandoned the previously announced policy of disarmament, but have also rekindled old projects such as “Star Wars”.
- Finally, a new doctrine in the United States contemplates the use of specific nuclear weapons against non-nuclear countries. This doctrine and the use of force against Iraq in disregard of the conclusions of UN inspectors (from the International Atomic Energy Agency – IAEA) on nuclear issues have weakened the best arguments on the practical uselessness of other countries seeking access to nuclear weapons.

In this scenario, it came as no surprise the complete failure of the UN Conference to review the Nuclear Non-Proliferation Treaty, which took place in May 2005.

With regard to Brazil, which was even identified as a cause of concern in the area of safeguards and the “flavor of the month” for international pressure to adhere to the Additional Protocol strengthening IAEA's safeguards, the situation has also improved:

- A decision was reached with the IAEA on the methods to be used to inspect the Rezende enrichment plant, which will not

disclose the technical details Brazil wanted to protect (a camera allows a view from the top of the centrifuges).

- The policy of preserving Brazil's enrichment technology was revealed and has been acknowledged as effective for non-proliferation, with no disclosure of information and no participation of Brazilian technicians in non-peaceful projects abroad.

The current oil price crisis and the problems of global warming associated with the greenhouse effect have led many countries to reconsider increasing the share of nuclear energy in their energy matrix over the next decades. Countries that kept their nuclear generation programs, such as China and Japan, have already announced their intention of intensifying them. Most countries chose extending the life span of existing reactors. Brazil seems inclined to resume the construction of Angra 3 and the 2030 Plan includes four additional nuclear power plants.

Therefore, it is inevitable that Brazil's (and, probably, Argentina's) adherence to the Additional Protocol, ratified by the IAEA to strengthen nuclear safeguards, will come again under discussion. This Protocol has already been signed by practically every country where nuclear energy plays a relevant role and it does not seem possible for Brazil to delay indefinitely its decision to adhere (or not) to it. It would be desirable to find a less intrusive way to eventually apply the Additional Protocol to Brazil.

Thus, Brazil's uranium reserves and mastery of the fuel cycle place the country in a privileged position regarding the use of nuclear energy. The world trend in non-proliferation indicates that this option will be closed to countries that are not able to master the technology over the next years.

## **Conclusions**

Projected energy demand for the next 30 years, even for less-than-desirable economic growth and taking into account efforts aimed at reducing energy intensity, reveals the need to add thermal energy to electricity generation, which today is predominantly hydroelectric. Nuclear energy should also have a share in generating electricity.

Overly optimistic forecasts of the reduction of the electricity intensity do not seem feasible in our time frame.

The cost of nuclear generation will probably remain competitive in a world scenario with oil prices above US\$ 40 per barrel. In Brazil, nuclear energy should also become competitive sometime during this period.

Environmentally, nuclear energy is once again being favored due to the growing pressure to reduce the emission of greenhouse gases. The storage of large quantities of carbon dioxide introduced the problem of long-term storage of waste (previously a nuclear prerogative) to other sources of

energy. The mass of the residues is fifty-thousand times greater than that from nuclear sources.

The line of reactors adopted by Brazil and the forecasted limited use of nuclear energy make it possible to postpone a solution to the problem of long-term waste disposal. The repositories for short- and medium-duration waste should be defined over the following years. The issue of dissociating CNEN from the industrial activities of the fuel cycle must also be solved. Special care must be given to the environmental impacts of mining activities, even that of non-nuclear materials.

The development of nuclear technology has already brought important gains for the country, affecting other areas of industrial activity – which, in turn, drive the domestic development of technologies that suffer from restrictions in the importation of techniques and equipment needed for other sectors.

Strategically, Brazil has uranium reserves and masters the technology to produce fuel. This makes its supply of electric energy less vulnerable, as it will probably depend more strongly on imported natural gas. The policies of non-proliferation of nuclear weapons have enormously restricted the development or importation of technology related to the fuel cycle. Brazil enjoys a privileged position in the development and responsible management of this technology and must strive to keep it active, because nuclear energy is certainly part of its energy future.

## Notes

- a This analysis can be global or by industry, as it was done here, for reasons of simplicity.
- b The values of GDP in PPP from 1980 to 2004 show practically the same relative behavior of the annual GDP values in real terms. This allows us to extend to the concept of purchasing power parity to the 1970-1979 period and project it for the following years.
- c The disparity between exchange rates in terms of purchasing power parity is a persistent reality in many countries, in spite of the economic openness that has been occurring. It is hoped, however, that if the process of economic internationalization is not reverted, this difference will disappear. Either way, the real value of the GDP is what should be taken into account.
- d The correspondence between both scales is not precise, but the approximation between the values in the upper scale and the observed values is quite good.

- e In 2005, for instance, the consumption of electricity grew more than the GDP (surprising government planners).
- f It should be noted that the change pointed out by the WWF study is equivalent to attaining, in 15 years, the same electricity/GDP ratio (in purchasing power parity) of Africa. Those who are more optimistic might say that Brazil would attain the level of Italy, which also has a low electricity/GDP ratio. But certainly, this way is not possible if the country continues to specialize in commodities. In any case, such a radical change in the economy of electric energy does not seem possible within the time frame suggested by the WWF.
- g For fission products, there is also the alternative of irradiation in accelerators to reduce residual activity.
- h In plants such as Angra 2, with only one turbine.

*ABSTRACT* – The perspectives of nuclear energy in Brazil is analyzed regarding demand, costs, environmental, technological and strategic aspects. The projected energy demand, even for a growth rate below the desired one and considering some efforts related to energy intensity reduction, shows the need of adding thermal energy to electricity generation, now predominantly hydraulic. Nuclear energy should have a share in this generation due to economical, environmental, technological and strategic reasons.

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