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Does Brazil need new nuclear power plants?

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ABSTRACT

In October 2008, the Brazilian Government announced plans to invest US$212 billion in the construction of nuclear power plants, totaling a joint capacity of 60,000 MW. Apart from this program, officials had already announced the completion of the construction of the nuclear plant Angra III; the construction of large-scale hydroelectric plans in the Amazon and the implantation of natural gas, biomass and coal thermoelectric plants in other regions throughout the country. Each of these projects has its proponents and its opponents, who bring forth concerns and create heated debates in the specialized forums. In this article, some of these concerns are explained, especially under the perspective of the comparative analysis of costs involved. Under such merit figures, the nuclear option, when compared to hydro plants, combined with conventional thermal and biomass-fueled plants, and even wind, to expand Brazilian power-generation capacity, does not appear as a priority.

1. Introduction

Power-generation projects should not be chosen under political or commercial pressures, such as is sometimes the case, but, rather, through judicious scrutiny based on comparisons between available alternatives, in considering the environmental impact, the possible exposure of the population to the risk of accidents, the foreseeable deadlines for the start of the operation, the guarantees regarding fuel supply (gas, oil, etc.), and whether there is enough large-scale industrial capacity for the enrichment of uranium and the manufacturing of fuel, in the case of nuclear power plants. Finally, but no less important, one must be aware of the costs, upon which the tariffs are based, to be paid for by the consumers.

In this article, we will discuss the aspects that intervene in the formation of the production costs of electricity. Power-generation costs are composed of part made up by fixed costs, from which the invested capital is recovered and repaid throughout depreciation lifetime of the generating power plant; and of another part made up by variable costs, composed of the expenses that are required to operate the plant. The fixed part (invested capital) includes expenses incurred in the implantation of the power plant (feasibility studies, engineering studies, equipment, preparation of the site, construction work, assembly, tests and commissioning), while the variable part is comprised of operation and maintenance expenses, insurance, taxes, salaries, overhead, etc., as well as fuels, in the case of thermal power plants.

The final costs (the sum of the fixed and variable costs) should be calculated in such a way as to allow for the setting up of tariffs that ensure return; i.e., both attractive to investors and fair to consumers. Hence, to keep the profits of the investor (or utility) from sacrificing the consumers, the internal rate of return (IRR) used to calculate the generation costs should be established by means of negotiations between the regulatory body and the utility or through tender bidding process to secure supply from investors, into which enter subjective criteria, such as "attractiveness" to the utility or investor and the "reasonability" to consumers. That is why there is an ethical imperative for the process to be completely transparent.

In practice, the internal rate of return reflects the opportunity cost of capital, i.e., the potential benefit that could be accrued from its allocation to next best alternative investment (Bitu and Born, 1993; Viscusi et al., 2000).

In capital-intensive projects, such as those of power sector, the main cost components are the amortization of the investment (cost of capital) and the cost of the fuel, when applicable. All other components (operational expenses, insurance, taxes, wages, etc.) have a less-intense effect. However, as the project approaches in the end of the accounting depreciation term, the importance of these expenses grows in comparison to the cost of capital.

The lifecycle of hydroelectric power plants surpasses the accounting depreciation term, which is conventionally set at 30 years. Hence, power plants that have already been paid off continue to generate energy at a cost that is reduced to the operational and maintenance expenses, insurances, wages and

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labor taxes. There are hydroelectric plants that were implanted in the beginning of the 20th century that continue to operate normally to this day, which is of great advantage to society, since people continue to benefit from the service without the burden of a new investment.

For coal-based thermoelectric plants, the cost of the fuel does not include the investments that must be done in the regions from which coal is extracted, to alleviate the environmental impacts (the contamination of rivers and water tables, air pollution, damage to public health, etc.). The environmental impacts of thermoelectric plants using natural gas—which are of considerably less importance than the coal-based plants—are also not computed in the cost of the power generated.

The fuel cost for nuclear power plants is made up of the sum of the costs of each of the steps in the uranium cycle, which ranges from mining up until the manufacturing of the fuel rods. In this composition, the most expensive stage is that of enriching the uranium, which comprises 36% of the costs. The impact of the cost of the uranium (U_3O_8) is around 27%.

The accounting depreciation term of nuclear power plants is equal to their shelf life (40 years, after which the plants must be decontaminated and decommissioned.

Decommissioning expenses should be brought to present value and included in the generation costs, so that a fund can be created with sufficient resources to cover those expenses. In Great Britain, for example, the government attributed a budget endowment of £2.47 billion (US$4.34 billion) for the term of 2007/2008 to the public organ that is responsible for decommissioning nuclear plants (Nuclear Decommissioning Authority).[1] Other components of the cost of nuclear power generation are the management of low- and medium-level waste, and that of the final disposal of high-level radioactive waste.

The facts show that planned costs of nuclear energy were optimistic when compared to actual costs for completed plants. As an example, the cost for the first new-generation pressurized water reactor that Areva, (French nuclear construction company) is building in Finland, is 50% higher than originally estimated (Rienstra, 2008). A recent assessment carried out by United States Congressional Budget Office (CBO, 2008) recognizes that "CBO's assumption about the cost of building new nuclear power plants in the United States is particularly uncertain because of the industry's history of construction cost overruns. For the 75 nuclear power plants built in the United States between 1966 and 1986, the average actual cost of construction exceeded the initial estimates by over 200%. Average overnight construction costs soared from projected 938 to actual 2959 US$/kW. Although no new nuclear power plants were proposed after the partial core meltdown at Three Mile Island in 1979, utilities attempted to complete more than 40 nuclear power projects already under way. For those plants, construction cost overruns exceeded 250%. The Federal Energy Regulatory Commission Office of Enforcement developed assessment of likely electricity costs in the coming years (FERC, 2008). In 2003–2004, its estimates for the capital cost for nuclear power plants ranged around 2000 US$/kW, whereas revised figures soared to 5000–8000 US$/kW. Two recent nuclear procurements in South Carolina and Georgia produced cost estimates of $5100 and $6400/kW, respectively, for the same Light Water Reactor technology. The reasons for the increase in building costs of nuclear power plants include rising global prices for materials, labor costs, the need to bring in additional safety requirements and the soaring cost of nuclear clean-up and waste disposal. These facts seem to indicate the possible existence of "negative learning curve" for nuclear plants, which may further harm its ability to compete with newcomers to the energy industry like wind and solar options.

For both the hydroelectric plants and the nuclear and thermal biomass and fossil fuel plants, the premiums paid to insurance companies are, on average, around 1% per year of the invested capital or of the insured amount.

In this article, we compute only bus bar cost of individual plant options, without quantifying synergies deriving from system integration. Thus, they do not take into account benefits such as secondary power from hydroelectric plants that allows for savings of fuel in complementary thermoelectric plants using natural gas, oil, biomass or even wind, all of which result from possible optimization in planning and operation in the framework of interconnected national power system.

The development of wind energy in Brazil is still in its initial stages when compared to energy from other sources. That is why wind energy is not explicitly included in the scope of the article. However, it is worth pointing out that based on surveys already conducted by the Brazilian Center for Research in Electrical Energy (CEPEL). Brazilian estimated potential exceeds 143 GW, especially along 8000 km of Atlantic coastline (EPE, 2006). The wind patterns seasonally complement the hydro patterns, in such a way that the capacity factor of the wind energy system could reach a level of, approximately, 20%, higher, therefore, than the average for systems of this kind. The cost for capacity contracted under the PROINFA (Alternative Energy Sources Incentive Program) has ranged from 107 to 137 US$/MWh [2] (MME, 2007). Learning and scale gains are expected to further reduce costs and enhance chances of wind power to compete, especially with the nuclear option.

These conditions would further favor the interconnection of the entire Brazilian electrical system in a grid of water–thermal–-wind energy, similar, to a certain extent, to the thermal-wind grid that is being studied in some European countries (Ummels et al., 2008).

2. Power-generation cost of the Angra III nuclear plant project

According to the Brazilian Nuclear Power Company, Eletronuclear, the Angra III plant will cost a total of US$4.66 billion (R$7.91 billion) of which US$330 million (R$560 million) have already been invested in the acquisition of the main mechanical components of the nuclear steam supply system (reactor vessel, pressurizers, steam generators, main coolant pumps and support structures) and some of the main components of the secondary circuit, such as the turbo-generator group, the main water feeding and condensation pumps, etc. (Eletronuclear, 2007).

In the calculations that follow, we have accepted that the internal return rate will be of 10% per year, and that Angra III will operate with the capacity factor that is expected by Eletronuclear (87%), a very optimistic number when compared, for example, to the French nuclear park, which is hardly 78%.[3] We have also considered that the State will be financing 70% of the budget for the conclusion of the construction, with an interest rate of 7.5% per year, with the remaining 30% as equity, at 8% per year, during the duration of the construction work. According to Eletronuclear, the implantation of Angra III will take 66 months—construction work, electromechanical setup, commissioning of the systems and preoperational tests—beginning with the job of putting down the building's basic concrete slab of the reactor building, and ending with the power tests of the plant.

[1] Nuclear Engineering International, 05 June, 2007.

[2] In this paper, an exchange rate of 1 US dollar to 1.7 R$ (Brazilian Real) has been adopted.

[3] Agence pour l'énergie nucléaire de l'OCDE (http://www.nea.fr).

Table 1
Power-generation costs of Angra III.

Installed capacity	1345 MW
Overnight cost, without interest during construction (IDC)—C_1	4,660,000
(US$1.000)	
Investor expenses (8% of C_1)	327,800
Direct cost—C_2	4,987,800
IDC (6 years, 7.5% p.a. of 70% of C_2+8% p.a. of 30% of C_2)	2,775,081
Investment capital—C_3	7,762,881
Annual costs (in thousands of dollars)	
Accounting depreciation in 40 years, with IRR = 10% p.a.→ CRF = 0.1022	
Annuity for cash payback	793,367
Insurance (1% of C_3, per year)	79,337
Maintenance (3% of C_1, per year)	139,800
Wages+overhead+management	25,294
Total annual costs	1,037,801
Power generation COSTS (in US$/MWh)	
Effect of annual costs (capacity factor = 87%)	101.2/MWh
Fuel	10.4/MWh
Expected cost of decommissioning and final disposal of high-level waste	1.76/MWh
Sum ⇒ generation cost of Angra III	US$ 113.36/ MWh

CRF: capital recovery factor.

Around the world, the duration of construction work of nuclear power plants is, on average, between 5 and 7 years/the interest during construction (IDC) is between 8% and 10% per year on 50% of the investment (the other 50% are composed of shareholder capital); the IRR is from 10% to 15% per year and the payback term is 40 years.

Decommissioning implies in future investments of between US$350 and US$500 per installed electric kW.[4] We have calculated that, in Brazil, the decommissioning expenses, in addition to the administrative costs of the low- and medium-level waste as well as that which will be spent in the future of the final disposal of high-level waste, will mean an impact of approximately US$1.76/MWh in the generation fee, throughout the plant's life cycle.

According to EPE, the fuel cost will remain at a mere US$10.4/MWh. It is important to emphasize that, since the end of the 1980s up until the middle of 2003, the price of uranium (U_3O_8) in the global market remained relatively stable, between US$10 and US$12 per pound. From then on, however, prices climbed rapidly, reaching the amount of US$130 per pound in 2007. Hence, there has been a growth of over 1000% in 4 years. Although the price of uranium has moderate impact in comparison to the other stages of the fuel cycle when it comes to establishing fuel costs, it is possible that the growing global demand results in an increase that makes this price an uncertainty factor.

In order to compare the costs of alternatives examined in this article in equal conditions, we are not considering that the government has decided to enter the investment already made (US$330 million) as dead capital to subsidize the electricity generated in Angra III.

As such, the calculation shown in Table 1 indicates how much the power generated in this nuclear plant will in fact cost to the society.

3. Natural gas power plants' generation cost

Calculations were performed for a typical combined cycle power plant of 500 MW capacity. The term for construction is of 36 months and the direct cost of the power plant amounts to US$1000 per installed electrical kW.

We have considered the thermodynamic efficiency of the system to be 50% and that the calorific value of the gas supplied to the power plant is of 36.8 MJ/m^3 (8800 kcal/m^3), thus the consumption of natural gas will be of 122.15×10^3 m^3/h.

We also consider that the capacity factor will be of 80% and that the price of gas will be US$7.5/10^6 BTU. It is worth mentioning that usually the price of natural gas follows somehow, in short and long terms, the price of oil and that these behave in a way that is virtually unpredictable. Based on these assumptions, we calculated that the generation cost of a natural gas power plant will be US$78.9/MWh.

As for environmental impacts, considering the mass balance of combustion reaction of natural gas (substantially methane), for such power plant operating with a capacity factor of 80%, it will release into the atmosphere approximately 2900 t of CO_2 a day.

4. Coal power plants' generation cost

Due to great demand, the investment costs in coal-based power plants have increased rapidly. For example, in China alone one coal-based thermal power plant is constructed every week (Harrabin, 2007). In Europe, in the United States and in Australia there are strong interests linked to coal-based thermoelectric plants, especially after considering the development of capture and CO_2 capture and storage technologies (Thambimuthu, 2008). Nevertheless, even if a technically safe and economically feasible solution is found for this, the capacity to store CO_2 in volumes that are compatible with global emissions in the long term is limited (Socolow, 2005).

In Brazil, although the coal is of low quality, with a very high percentage of ash and heating value of only 10–15 MJ/kg, power generation based on coal has been making a comeback.

The investment cost in a power plant that has been projected to be installed in Brazil, to operate using local coal, is of approximately US$2150/installed electrical kW. The period for construction is of roughly 48 months, though this can take up to 51 months, depending on how long it takes to obtain the necessary license.

The cost of coal varies according to the extraction method, the number and width of the layers found in the mine, among other factors. For coal from open-pit mines, that has not been treated or sieved, and pulverized for burning, the price is around US$20/t. Treated and sieved coal can cost up to US$35/t (Rezende, 2008).

The coal that costs US$20/t has a heating value of 13.8 MJ/kg (3300 kcal/kg), so that, with a thermodynamic efficiency of 33%, the consumption will be of around 1000 kg/MWh. Based on these figures, the generation cost of a coal power plant is estimated at US$134/MWh.

Coal combustion is extremely polluting, implicating in emissions of CO_2; SO_2; H_2O; NO; NO_2 and ash, among others.

Operating with a capacity factor of 50%, a coal power plant of 350 MW will emit, per day, about 1800 t of CO_2, aside from the ash and other byproducts.

In our opinion, licenses should not longer be given for the construction of new power plants using coal and only those that are already in existence should be authorized to operate until the end of their lifetimes.

5. Biomass power plants' (sugarcane bagasse) generation cost

Although sugarcane bagasse market is still incipient, among other reasons due to logistic costs and absence of infrastructure,

[4] IEA Energy Technology Essentials, Nuclear Power, March 2007.

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prices average around US$15/t. Sugarcane harvest season extends over an 8-month-period, usually from April to November, in Brazilian Southeast, and nicely complements the rain season that usually spreads from November to April. Hence, in principle, plants using bagasse can operate with a capacity factor of 60%, and in synergy with the hydroelectric power plants, all interconnected to the national power grid. Another synergy occurs with the Brazilian automobile fleet, which is to a large extent fueled by ethanol (Kamimura and Sauer, 2008), which alone induces the production of enough bagasse to add 4750 MW to the capacity of the bagasse biomass power plant, nowadays (EPE, 2006). Assessments indicate that, by 2012 Brazilian sugarcane industry with the combined use of 75% of bagasse and 50% of leaves and tops in cogeneration scheme will be able to export to the power system 10.000 MW average capacity (Unica, 2008).

The heating value of bagasse is 2200 kcal/kg. Many biomass power plants that use bagasse already operate with 81 bar boilers, hence, the system's thermodynamic efficiencies is around 35%.

The direct cost of building a power plant of this type is approximately US$1600 per installed electrical kW. Based on these figures, we have calculated that the generation cost of biomass power plants using bagasse is around US$74/MWh.

6. Hydroelectric power plants

Table 2 summarizes the Brazilian hydroelectric potential. Table 3 shows that the largest part of the non-exploited potential can be found in the Amazon. Large part of this potential can be technically and environmentally tapped, especially if appropriate regulatory framework and negotiation processes required to overcome social and environmental questions are implemented. Aside from the large-scale hydropower plants, there are also the small hydroelectric plants, whose combined potential is as high as 17.5 GW.

In Europe, hydropower plants—large and small plants—contributes 17% to the production of electricity, ranging from 99% in Norway, 76% in Switzerland, 65% in Austria, 51% in Sweden, 23% in France, 12% in Czech Republic, 6% in Poland, 4% in Germany, 3% in Britain and less in some other countries and small hydropower plants contributes 7% of the total hydropower generation (Hydro Power and Dams World Atlas, 2001).

In Brazil, small power plants could play a very important role in distributed power-generation projects and multiple use projects, by supplying water for irrigation and for domestic and industrial use.

There are clear advantages to hydroelectric power plants. Instead of using fuels, they operate through the action of solar evaporation and of the gravity field, which is costless. Also, contrary to what certain environmental activists claim, they are much "cleaner" than thermal power plants. In fact, aside from the carbon dioxide emissions from the use of fossil fuels in the construction, fabrication and transportation of the electromechanical components—which is marginal, since it occurs only during the construction of the power plant—the greenhouse gases emitted by hydroelectric plants come from the decomposition of organic matter left behind in the reservoirs. The main gas released is methane, which get dissolved in the water. The largest amounts of these gases are emitted at a maximum distance of 10–15 m from the discharge of the turbines as a consequence of the sprinkling or spraying of the turbinated water, creating an aerosol of dissolved gases. This problem can be alleviated by mounting reinforced concrete shells leaned over the end of the discharge tunnels so as to intercept and return the droplets of aerosol to the water flow, downstream. Furthermore, the presence of dissolved gases in the reservoirs would be much slighter if those responsible for the construction of the hydropower units cleared out the areas to be flooded beforehand, so as to remove all wood and organic matter. If the projects respect these requirements, the emissions of hydropower reservoirs will be equal to the emissions of any natural lake or lagoon.

Finally, hydropower project concessions could end up becoming the greatest allies of the Amazonian ecosystem because deforestation would jeopardize the water regime in the region, thereby bringing serious losses to the hydropower generation itself.

Table 2
Brazilian hydroelectric potential and the development until 2007.

Hydroelectric exploitation	GW	Percent
Power plants in operation (developed potential, 2007)	71.2	27.3
Power plants in the expansion plans, up until 2025	98.6	37.7
Power plants planned for after 2025	73.7	28.3
Subtotal	243.5	93.3
Potential of small hydroelectric power plants	17.5	6.7
Total	261.0	100.0

Source: Brazilian Agency for Energy Research (Empresa Brasileira de Pesquisas Energéticas—EPE).

Table 3
Geographic distribution of the potential to be exploited.

Region	North	Northeast	Center-west	Southeast	South
Percent	65	3	3	8	21

Source: Brazilian Agency for Energy Research (Empresa Brasileira de Pesquisas Energéticas—EPE).

7. Power-generation costs of Santo Antônio and Jirau power plants on Madeira River

The Santo Antônio and Jirau hydropower projects are good examples of the not yet exploited potential in Brazil. As such, we can consider the power-generation cost of these power plants to be the representative cost of the large part of the remaining potential of Brazilian hydropower plants, having an estimated capital investment cost of around US$1600 per installed kW (Table 4). Assessments indicate that up to 75 GW of additional capacity could be developed with investment cost of up to 1500 US$/kW (EPE, 2006).

Table 4
Power-generation cost of Santo Antônio and Jirau.

Total capacity of both power plants	6450 MW
Capital required for investment (in thousands of dollars)	10,300,000
Annual costs (in thousands of dollars) Accounting depreciation in 30 years, with IRR = 10% p.a. → CRF = 0.106)	
Annuity for payback	1,091,800
Insurance	96,500
Maintenance	86,470
Wages+overhead+management	14,665
Total annual costs	1,289,435
Power generation costs (in US$/MWh)	
Effect of annual costs (with a capacity factor of 50%)	45.6
Sum ⇒ generation cost of the Rio Madeira complex	US$45.6/MWh

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With installed capacity of 3150 MW (Santo Antônio) and 3300 MW (Jirau), these hydroelectric plants are situated on the Madeira River in the state of Rondônia, in the Amazon rainforest. They will be made up of small stream barriers, power stations, spillways and bulb turbines.

The innovative aspect of the project is the employment of turbines of this kind in large-scale hydroelectric plants. Thanks to this, both plants will be of low head, with reservoirs that will flood areas of 271 km^2 (Santo Antônio) and 258 km^2 (Jirau), relatively small for hydropower plants of this size.

The original plan also included some floodgates to create a waterway connecting the Bolivian interior to the Amazon River, with an extension of approximately 4000 km.

The total investment at implantation of both power plants will be of US$10.3 billion, including the interest rates during construction and the installation expenses of the construction sites and the mitigation of environmental impacts.

Table 4 shows the calculation for the combined power-generation cost of both power plants, based on similar financial conditions to those of Angra III and to natural gas and coal thermal power plants.

The beginning of the construction work for Santo Antônio had been planned for October 2008, and the first machine has been scheduled to start the testing stage in mid 2012. Construction work for Jirau has been scheduled to start in 2009, with the first turbine test in 2013.

8. Final remarks and conclusions

The extension and the perspectives for making use of Brazil's hydropower potential in the short, medium and long term, combined with thermal, biomass and wind complementation, lead to the conclusion that the program to build new nuclear power plants announced by the Brazilian Government is not a priority.

The country, therefore, has practically no need for large-scale thermal power plants, since, as shown above in Table 2, the hydropower potential is of 261.1 GW, of which merely 71.2 GW (or 27.3% of the total) are being made use of. An efficient thermal complementation for the hydropower system can be ensured by rational synergy projects between the regimes of a number of water basins, with the sugarcane harvests and integration. When a complementation to the water regime becomes necessary, the thermal and natural gas power plants would come forth with fuel supplies that would allow for a flexible operation. In fact, optimization of Brazilian hydrothermal system generation cost require, under current conditions, that new gas-fired power plants should not incur in fixed fuel supply cost, and should rather depend only on flexible supply, either from the international liquefied natural gas (LNG) market or from nearby non-associated natural gas wells.

Wind power option holds a potential to contribute to further optimize the Brazilian Integrated Power System expansion, if policies to enhance domestic technology and industrial capacity are implemented in order to reduce costs, as expected from typical learning and scale curves for infant technologies. With research, development programs as well as industrial scale incentive programs relying on budgets of only a small fraction of that envisioned for nuclear power, wind power has large chance of becoming an important contributor to optimally expand power-generation capacity in Brazil.

The potential decision to finish construction work on Angra III simply to justify the existing sunk could prove to be a mistake. When estimated power-generation cost of the Madeira River Complex are compared to those for the Angra III power plant, it becomes clear that, to generate the same block of energy that the latter would produce in 1 year of operation, for approximately US$1.16 billion, the power plants on the Madeira River would spend only US$472 million. This would, therefore, involve savings of US$688 million a year (Table 5).

Table 5
Cost and annual production by typical power plant.

Project	Energy cost	Annual production[a] (MWh)	Term of construction work (years)
Angra III (1345 MW)	US$113/MWh	10,258,000	~7
Natural gas (500 MW)	US$79/MWh	1,315,000	~3
Coal (350 MW)	US$134/MWh	1,534,000	~4
Sugarcane bagasse (12 MW)	US$74/MWh	63,000	~3
Madeira River (6450 MW)	US$46/MWh	28,270,350	~5

[a] Capacity factors: Angra III = 0.87; natural gas = 0.80; coal = 0.50 and bagasse = 0.60.

As for technological development, it is important to note that the purpose of nuclear power plants is to generate power and not to develop technology. Eletronuclear, already has highly qualified teams that acquired a great deal of experience in the operation and maintenance of the nuclear power plants currently in operation in Brazil, Angra I and Angra II. These teams are constantly being renewed, with younger employees joining the company and being trained and educated by the more experienced employees who are close to retirement age. Angra III is not required in order to preserve this expertise. To build this power station with the purpose of developing project technology and constructing nuclear power plants would be the equivalent of buying an Airbus A380, which may be very well piloted by pilots who were trained in Brazil but who do not have—indeed could not have—the incumbency of designing and building airplanes. In fact, Brazilian airline companies have always purchased and operated modern planes, however, the Brazilian aeronautical industry only developed after the creation of the Institute of Aeronautical Technology, which encouraged the creation of Embraer and other companies that are included in its production chain.

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