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Must Nuclear Energy be Increased on Brazilian Energy Mix in a Post-COVID-19 World?

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ABSTRACT

This paper aims to discuss the convenience and feasibility of increasing the nuclear energy participation on the Brazilian energy mix, amid a national context of climate change, scarcity of natural resources necessary to baseload energy generation, particularly hydropower, discussions on a possible restart and expansion of Brazilian nuclear program, whilst the population still suffers socioeconomic impacts resulting from COVID-19 pandemic as well as the pre-pandemic economic crisis. The work proposes four analysis axes: environmental factors, economic, safety/legislation and technological aspects, and through bibliographic research in scientific articles published in journals, theses, dissertations, laws, regulations and international recommendations, it was possible, as a result of the research, to draw an optimistic overview of a possible future expansion of the Brazilian nuclear program, considering the advantages and challenges of using the nuclear alternative when compared to other energy sources.

Keywords: **Nuclear Energy, Brazilian Energy Mix, Climate Change.**

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1. INTRODUCTION

Modern civilization is possible because people have learned how to change energy from one form to another and then work. In this context, the energy and energy matrix could understand as measurable and calculable values, which enable the achievement of the most diverse goals of society, facilitating human work, economic growth, and enabling poverty reduction [1] [3].

The energy used daily to meet energy needs (demand), whether of an individual, a city, a country, or the world, using the different types of energy sources available, in different proportions, depending on the case, form what is defined commonly as an energy matrix [1] [2].

To achieve sustainability in energy, human society must face the challenge of initiating a significant transformation of the energy matrix due to the possible catastrophic effects of climate change. Their increasingly perceived consequence leave little time for effective implementation [5].

Alternative clean energy generation technologies, such as solar photovoltaic (PV) and wind, are currently the flagship in implementing energy mix changes, with a growing percentage on the national energy mix in Brazil. However, these alternatives need further development to reduce the effects of intermittency, increasing the capacity factor to make them truly attractive for replacing the baseload of the national system, which currently relies on hydropower, an alternative highly dependent on climate conditions [6].

Another challenging aspect of solar PV and wind energies is their supply dependence - solar panels and magnets based on rare earth, from producing countries such as China, the United States, and others, are still a problem to be overcome, in addition to its need for large areas for high energy production demanded by cities and agriculture [7].

The COVID-19 pandemic brought a new context in which an economic crisis that, on the one hand, reduced the energy demand for industrial and commercial applications and resulted in the scarcity of global supplies, owing to several factors such as logistics difficulties, reduced manufacturing capabilities and political issues [8].

Amid this challenging context, this paper aims to contribute to the discussion on the convenience and feasibility of increasing nuclear energy participation in the Brazilian energy mix, considering climate change, scarcity of natural resources necessary to base energy generation, mainly hydropower. As also to discuss a possible restart and expansion of the Brazilian nuclear program, at the same time, the population still suffers socio-economic impacts resulting from the COVID-19 pandemic and the pre-pandemic economic crisis.

2. MATERIALS AND METHODS

To answer the question: should nuclear energy increase its participation in the Brazilian energy matrix? The work proposes four analysis axes: environmental factors, economic, safety/legislation and technological aspects, and through bibliographic research in scientific articles published in journals, theses, laws, regulations, and international recommendations. In terms of environmental aspects, the paper argues the emissions of greenhouse gases generated by nuclear energy, considering the technology used here, Uranium-based Generation II and Generation II+. Other energy alternatives increase the country's need to achieve the goals of international agreements to reduce CO2 from burning fossil fuels.

Regarding economic aspects, costs of building, operation and decommissioning compare during the life cycle of the different energy sources. In terms of safety and legislation, regulatory regimes are compared mainly in terms of safety and security requirements.

The abundant natural resources deserve special attention, as Brazil has one of the most significant U, Th, and Li minerals reserves. In technological aspects, in addition to knowledge and mastery of the nuclear fuel cycle, considering that its beginning was in the 40s with the pioneers of ORQUIMA, through the interaction of Universities with various institutes from CNEN, the Brazilian Navy and other sectors of industry. Figure 1 shows a flowchart of the study:

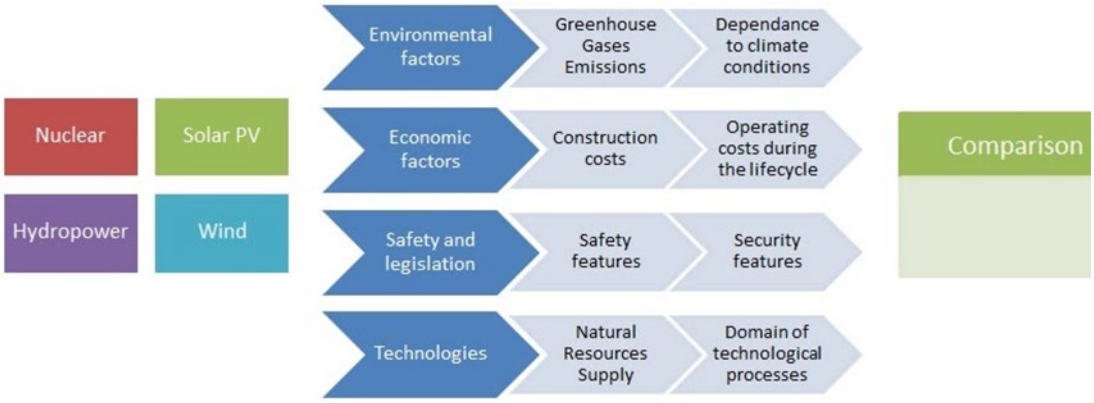
3. RESULTS AND DISCUSSION

The elaboration of the results was based on the studies carried out with Energy Security, climate change, evaluation of modular nuclear reactors and the primarily associated legislation as follows:

3.1. Brazilian energy security

From the economic interpretation, energy becomes a good, which in general is poorly distributed, expensive, and subject to price fluctuations. From the oil crisis of the 1970s, this vision made energy become a national security issue, more or less, depending on geographic location, amount of natural resources, international relations, political system, economic and ideological arrangements [4].

Figure 1. Structure of methodology steps for this study.



This new question added the physical definition of the energy matrix to the evaluation component called energy security, which has numerous definitions; the International Energy Agency (IEA) defines energy security as "the uninterrupted availability of energy sources at an affordable price". Asia-Pacific Energy Research Center (APERC) defines it as “the ability of an economy to ensure the availability of the supply of energy resources in a sustainable and timely manner with the price of energy at a level that will not adversely affect the economic performance of the economy. ", there are several others in the literature, but that does not stray too far from these positions [9-11].

Based on these definitions and others, a succinct way of approaching energy security was built, called in English four “As”: 1) Availability, which measures the extent to which the provider has the necessary resources (material, personnel, and technology) to meet customer needs. 2) Affordability, measuring how the provider will charge for the service, always matching the customer's ability to pay for the services. 3) Acceptability, checking to what extent the client feels comfortable with the most immutable characteristics of the provider and vice versa. 4) Geopolitical accessibility (accessibility) is determined by the ease with which the customer can physically (and safely) reach the provider's location and vice versa. To these four aspects from the first decade of the century, a fifth item was added, which is: 5) to identify the energy sustainability of the matrix or "the capacity for sustainable development of the energy system in a low carbon, clean mode and optimized" [2,5,16].

Analyzing the description and values of the energy matrix in Brazil (Tables 1 and 2), in the period 2019 and 2020, and additional information obtained from the National Energy Balance (BEN), we can obtain some data for analysis [7].

Table 1: Total energy supply 2019 – 2020 – Brazil.

	Year		
Source (Mtep)	**2019**	**2020**	**Δ20/19**
Renewables	**135,6**	**139,1**	**2,5**
Sugarcane biomass	52,8	54,9	3,8
Hydraulic Power (1)	36,4	36,2	-0,6
Vegetable firewood and Charcoal	25,7	25,7	0,0
Bleach and Other Renewables	20,7	22,2	6,8
Non-renewable	**158,3**	**148,5**	**-6,6**
Petroleum and derivatives	100,9	95,2	-6,0
Natural gas	35,9	33,8	-6,2
Mineral coal	15,4	14	-10,0
Uranium (U3O8)	4,3	3,7	-16,2
Other Non-renewable	1,8	1,7	-5,9

(1) Includes import of electricity from a hydraulic source

From the tables and additional information:

1) Since 1 Mtoe (megatons of oil equivalent) is worth 11,667 GWh (Giga watt-hour), we found that the production of electricity in 2020 is equivalent to 53.244 Mtoe, or about 18.55% of the total energy consumed in Brazil.

2) The most significant energy consumers in Brazil are industries consuming 32.1% of all energy and the transport area consuming 31.2% of all energy.

3) Of the energy consumed in Brazil, 48.4% comes from renewable sources and 51.6% from non-renewable sources. It should be clarified that renewable sources: sugarcane biomass, firewood and charcoal account for 57.9% of the total used.

4) analyzing the electric matrix, we have that hydroelectric energy production corresponds to 63.8% of the total electric energy produced and the other renewables to 19.9%.

5) Wind and solar energy account for 10.90% of the total supply of electricity produced.

6) The energy generated by nuclear power plants corresponds to 2.26% of the total electric energy production.

7) Energy generated by natural gas and oil accounts for 9.85% of the total electric energy supply produced.

Table 2: Total Electric Power Generation 2019 – 2020 Brazil

Source (GWh)	**Year**		
	2019	**2020**	**Δ20/19**
hydroelectric	397877	396327	-0,4
Natural gas	60448	53464	-13,1
wind	55986	57051	1,9
Biomass (2)	52543	56167	6,5
Nuclear	16129	14053	-14,8
Steam coal	15327	11946	-28,3
Petroleum Derivatives (3)	6926	7745	10,6
Solar Photovoltaic	6655	10750	38,1
Other Non-renewable	14438	13696	-5,4
Total generation	626328	621198	-0,8
hydroelectric	397877	396327	-0,4

1 - Includes distributed generation; 2 - Includes firewood, sugarcane bagasse, biodiesel and bleach; 3 - Includes diesel oil and fuel oil; 4 - Includes other primary sources, coke oven gas and other secondary sources.

(1)

From the analysis of the Tables 1 and 2 , we can state that:

1st) Brazil has an energy matrix with a large share of renewables in the energy matrix, much better than the world average of 14.2%, as well as that of the Organization for Economic Cooperation and Development (OECD) countries of 10.8% [13].

2nd) Electricity consumption is below that of countries with a Human Development Index above 0.8 (very high), considered as 4,000 kWh *per capita* (minimum), while the Brazilian consumption is 2,698 kWh / *per capita* [47] [48].

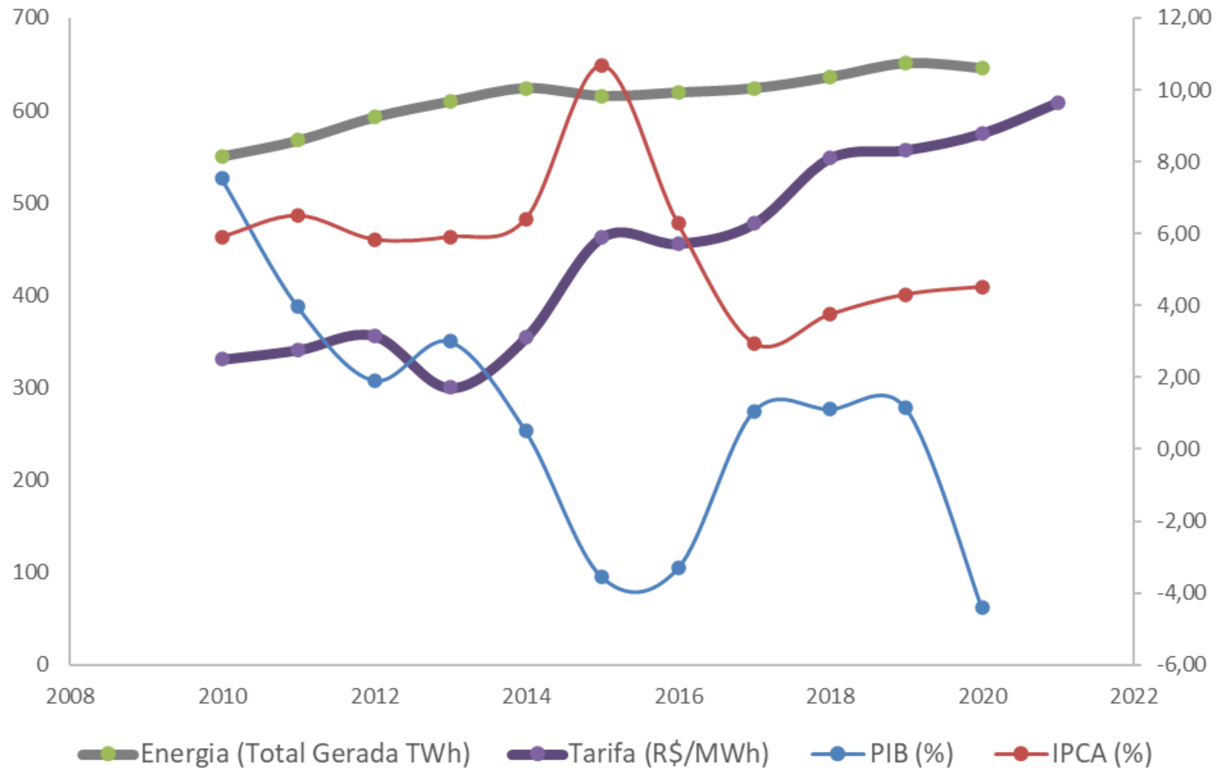
3rd) The cost of electricity in Brazil has been behaving in a way that follows inflation, see Figure 2, except in the period 2013 and 2014 due to disorganized government actions at the time, added to a period of drought in subsequent years.

4th) Since 2010, there have been cost pressures on electricity due to the need to activate thermoelectric plants using gas and other fossil fuels to deal with the issue of drought and reduction in the capacity of hydroelectric reservoirs; Fig. 3 shows this variation in the capacity of generation for each of the regions of Brazil, note that there is no seasonal compensation, that is, all regions suffer variations in generation capacity at the exact times.

5th) The values of total electric power generation have not been pressured, at least until today, due to the recession and the small growth of the Brazilian economy as of 2014.

However, the current stability of energy consumption, maintained by the possibility of generation via thermoelectric power plants, should not continue for much longer, under the risk of Brazil entering an economic situation of stagflation, which will generate social pressures due to the natural increase in inequality, poverty, and hunger.

Figure 2: Variations in economic indicators between 2010 and 2020 x average residential energy tariff. Source: ANEEL [14] e Carvalho [15]



3.1.1 Risks until 2050

As of 2010, the generation of electric energy through thermoelectric plants stabilizes the supply but creates pressure that raises the costs of the economy. It is essential to highlight that the values of the total electric power generation did not grow due to the recession and the consequent low growth of the Brazilian economy from 2014. However, if we analyze the period until 2050, worrying problems are foreseeable:

i. Brazil will only be able to grow economically if there is an energy supply, proactively, if it increases its energy matrix, specifically the production of electric energy.

ii. The Brazilian government, through the defunct Secretariat for Strategic Studies (SAE), in the Brazil 2040 Study, was already aware of the risks in generating electricity via hydroelectric plants caused by climate change. Studies showed that depending on the variation in the temperature increase on the planet, and specific basins could lose up to 40% of their flow, more catastrophic forecasts pointed to a 70% reduction [12] [17] [18].

iii. Studies developed within the scope of Universities and in the IPCC 2021 report corroborate and expand the vision of the forecasts [7,19,20].

iv. These forecasts also alert to the situation of variation in the rhythms and potentials of the wind system and the level of insolation in different regions of Brazil [21-24]

v. There is also a concern that burdensome rainfall regimes also create problems in controlling the plants. Thermal plants in Brazil have been showing an operating cost pressure generated by the increase in the cost of gas, resulting from the greater demand for this fuel by developed countries, which seek to reduce the carbon footprint of the electricity used by them, generated originally and preferably, from burning coal, which is highly polluting.

vii. There is a limitation to the development of energy solutions via thermonuclear plants, as the National Energy Plan 2050 of the Ministry of Mines and Energy in conjunction with the Energy Research Company [35,36], states: "However, it should be noted that the time required for licensing and construction of a new plant, the national fuel supply capacity and the scale of the supply industry are factors that end up defining thermonuclear expansion, in addition to Angra complex, at 10 GW in the horizon of the PNE 2050."

viii. Brazil needs to determine how much and from what sources the country seeks to cover both energies need to maintain a compatible growth rate, something like 4% per year (undetermined value, depending on the type of companies), and the amount of energy which will have to be added to the current capacity to compensate for the foreseeable losses in the generation of the existing hydroelectric plants (this is talking about something like 80 GWh).

ix. Emphasize that the water storage capacity must grow and be used to maintain the necessities of life (agriculture and livestock, sanitation, and human consumption).

x. Paying attention to the fact that biomass is also directly dependent on water and may suffer reductions in productivity with the increase in the planet's temperature, energy via biomass in Brazil is responsible for 57.9% of the total use of renewable energy.

3.2. Environmental Aspects - Climate Change

Looking from the environmental side, the IPCC defines climate change as a statistically significant variation in an average climate parameter that persists over an extended period, typically decades or more. In abstract terms, climate change can be caused by natural processes, and indeed in the Earth's past, there have been essential variations in climate, such as glacial periods. However, the recent change has its cause in the set of human and natural activities.[27]

Data from the Brazilian Panel on Climate Change (a scientific body created by the Ministries of Science and Technology and the Environment) indicate that Brazil could lose around 11 million hectares of arable land due to climate change by 2030. According to estimates in a report of the IPCC released in 2014, the combination of the increase in the average temperature and the scarcity of water resources would considerably reduce the cultivation of food [28]. As there is in Brazil a direct relationship between the water problem and the supply of electricity, due to its percentage of 65.2% in electricity generation by hydroelectricity [29], all issues that affect the economy, due to a reduction in energy supply, must be considered for the Post-COVID 19 world, when it is established that the Brazilian energy matrix must maintain the same percentage of electricity from hydroelectricity.

3.3. Energy Solutions for Brazil – Small and Medium Nuclear Reactors

The existence of uranium and thorium fuel cycle technology in Brazil allows us to realize the importance of small and medium-sized nuclear reactors in meeting energy needs. The International Atomic Energy Agency (IAEA) defines 'small' as less than 300 MWe and up to around 700 MWe as 'medium' - including many 20th century operating units. Together, they have been called by the IAEA Small and Medium Reactors (SMRs). However, the term “SMR” is commonly used as an acronym for “small modular reactor”, designed for construction in series and collectively to comprise a large nuclear power plant. [30,31]

There are two types of nuclear reactors, in practical terms, being the power reactor and research reactor. The first uses the energy released in nuclear reactions to produce electrical energy, and the second uses the radiation generated in the nuclear reaction for various applications. In Brazil, there are both types of reactors. Angra 1 and 2 and under construction 3, in addition to the construction of the Brazilian Multipurpose Reactor (RMB), which is a research reactor with various purposes, among which we can highlight the production of radioisotopes for use in medicine and industry, carrying out testing of nuclear materials and fuels for power reactors, use of neutron beams for scientific and technological research in different areas of science, training in the nuclear area with the training of personnel for operation and maintenance of power reactors.

With the RMB, Brazil will become self-sufficient in producing radioisotopes and radiopharmaceuticals, essential substances in nuclear medicine, a medical specialist that today offers the most excellent chances of accurate diagnosis and treatment of relevant diseases such as cancer. It has essential applications in cardiac problems, assessment of brain activities, among others. [33]

In the scope of national defense, we have the Nuclear Power Generation Laboratory (LABGENE), which represents an essential part of the Navy's Nuclear Program (PNM), being the prototype on the land of the nuclear plant of the future Brazilian nuclear-powered submarine (SN-BR).

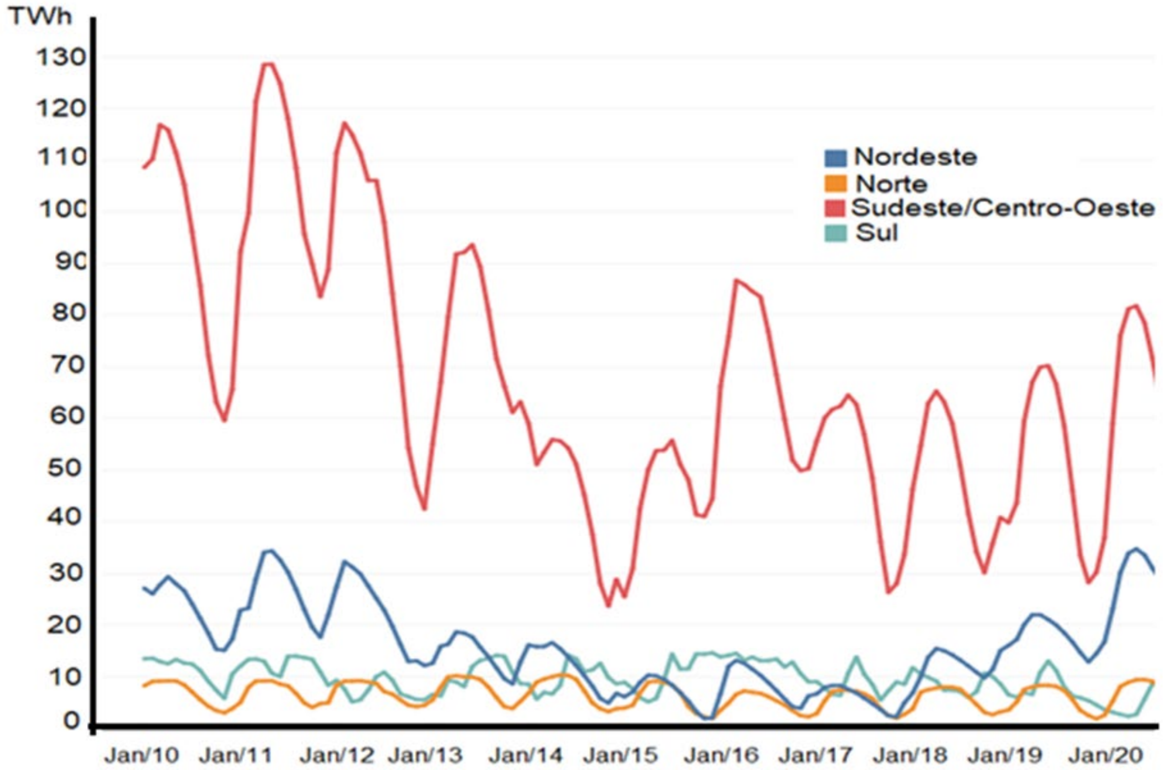
LABGENE was conceived as a prototype, on land and in full scale, of the propulsion systems that will be installed in the future Brazilian Nuclear Submarine (SN-BR) to enable the simulation, in optimal safety conditions, of the operation of the reactor. The various electromechanical systems were integrated into it before its installation onboard the SN-BR. In this context, an important point to be highlighted is that, due to its dual-use characteristic, LABGENE will serve as a base and laboratory for other projects of nuclear power reactors in Brazil. [34]

Both are included in the concepts of Small Modular Reactors, knowing that nuclear technology is constantly evolving and seeking to assimilate what has been learned in past experiences, it can be predicted that there will be an approach to goals such as sustainability: more efficient use of fuel and reduced nuclear waste generation, safety and reliability: reduced accident risks and increased efficiency and resistance to proliferation; and physical security: enhanced physical protection against terrorist attacks and technology that does not allow the development of atomic weapons. [35]

3.4. Legal aspects of nuclear safety

Concerning the legal and regulatory aspects of nuclear safety and physical nuclear safety, it should be noted that the peaceful character of the Brazilian nuclear program is expressly guided by the Constitution, which advocates the state monopoly of the nuclear sector and the strictly peaceful purpose of use of nuclear technology in the country, only in the forms authorized by the National Congress [36]. Critical nuclear infrastructure is heavily regulated, with 59 nuclear standards and 12 regulatory positions in place [37].

Figure 3 : STORED ENERGY – ONS Technical Database based on levels verified in reservoirs managed by ONS. Source: National Electric System Operator (ONS) [32].



Brazil is a signatory to the two main international conventions about safety: the Nuclear Safety Convention and the Convention on Physical Protection of Nuclear Materials, implemented in the national legal system through Decrees No. 2,648, of July 1, 1988 [38] and nº95, of April 16, 1991, respectively [39].

Among the obligations arising from both conventions, the country's obligation to maintain a high level of safety over its nuclear materials and installations through a regime that includes: 1) a legal and regulatory framework, 2) assessment of the safety actions implemented by the holders of licenses to operate nuclear installations, 3) treatment and reporting of incidents, 4) emergency plans, 5) enforcement measures and sanctions.

There is also an extensive infra-constitutional standardization that regulates and details what the Constitution advocates. Table 3 summarizes the main legal instruments that regulate the use of nuclear energy in the country, specifically in the aspects of nuclear safety and physical protection: From the data in Table 3, Brazil has a legal and regulatory framework that, in theory, allows the State to control the actions of protection and safety of nuclear materials and facilities in the Brazilian nuclear program, through actions of licensing, inspection and control carried out by the regulatory body and verified by national and international control bodies. This legal and regulatory structure adheres to international treaties to which Brazil is a party representing a safe use of nuclear energy concerning regulatory aspects.

Preliminary results of the study indicate that nuclear energy, despite a low cost-effective when compared to other energy sources, especially in the construction phase of a power reactor, ordinarily takes a long time and needs high financial contributions, is a competitive alternative to energy production, due to the: 1) abundance of natural resources, 2) low greenhouse gases emissions, 3) independence to climate conditions 4) a strong regulation in relation safety and security of nuclear materials and facilities, as well as the management nuclear' residue.

Table 3: National laws and regulations on nuclear safety and security - summary.

Regulation type/number and date	**Ementum/ Featured Articles**
Law nº 4.118, de 7/8/62 [40]	Establishes the definition of nuclear material and creates the National Nuclear Energy Commission (CNEN)
Law nº 6.453, de 17/10/77 [41]	Criminally typifies various offenses related to nuclear materials and facilities, transportation facilities and import/export of nuclear materials
Law nº 7.781, de 27/06/89 [42]	Defines CNEN's competences
Law nº 9.605, de 12 /02/98 [43]	Law 9,605 ("Environmental Crimes Law"), in its Article 56, paragraph 2, provides penalties for those who fail to comply with laws, rules and regulations relating to the activities of packaging, import, export, storage and transport of toxic, dangerous or harmful to health, with an increase in the penalty if the offense involves nuclear or radioactive materials.
Decree nº 9.600, de 5/12/18 [44]	It consolidates the guidelines of the Brazilian Nuclear Policy contained in Law 4.118, mentions nuclear safety and physical protection as guiding principles and also provides incentives for training, development and innovation in these areas
Resolution CNEN 11/99, de 2/09/99 (Norma CNEN NN 2.02) [45]	Provides for accounting and control of nuclear materials
Resolution CNEN 253/19, de 26/11/19(Norma CNEN NN-2.01) [46]	Provides for the principles and requirements of physical protection applicable to nuclear materials and facilities

4. CONCLUSION

The results obtained from the study demonstrate the advantages of the use of nuclear energy in Brazil. The nation has several unique features (such as natural resources, technology and legislation) that make possible sustainable use of nuclear energy. The introduction of electricity production by nuclear energy proves indispensable to assure our sustainability in the medium and long time.

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