

NUCLEAR ENERGY: PROBLEM OR SOLUTION FOR THE BRAZILIAN ELECTRICITY SECTOR?

ENERGIA NUCLEAR: PROBLEMA OU SOLUÇÃO PARA O SETOR ELÉTRICO BRASILEIRO?

ENERGÍA NUCLEAR: ¿PROBLEMA O SOLUCIÓN PARA EL SECTOR ELÉCTRICO BRASILEÑO?



<https://doi.org/10.56238/sevned2026.019-009>

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ABSTRACT

The present article explores nuclear energy in the context of the Brazilian electrical system, beginning with a global overview that highlights the importance of this energy source in the global energy matrix, emphasizing its crucial role in diversifying energy sources and mitigating carbon emissions. The study also examines this global perspective and the specific situation in Brazil, where the contribution of nuclear energy remains modest. Furthermore, the inherent qualities of this source are noted, such as its energy density and its capacity to provide a continuous and reliable energy supply. Additionally, the associated benefits are analyzed, including the reduction of dependence on fossil fuels and the decrease in greenhouse gas emissions. However, the risks involved are also addressed, such as the management of radioactive waste and the potential for nuclear accidents. Thus, there is a balance observed between the qualities and potential risks of this alternative, enabling the implementation of strategies to ensure energy security within the Brazilian electrical system.

Keywords: Nuclear Energy. Electrical System. Energy Diversification. Carbon Emissions.

RESUMO

O presente artigo explora a energia nuclear no contexto do sistema elétrico brasileiro, iniciando com um panorama global que ressalta a importância dessa fonte energética na matriz elétrica mundial, sublinhando seu papel crucial na diversificação das fontes de energia e na mitigação das emissões de carbono. O estudo também examina essa visão global e a situação específica do Brasil, onde a contribuição da energia nuclear ainda é modesta. Ademais, constata-se as qualidades inerentes a essa fonte, como sua densidade energética e a capacidade de fornecer uma energia contínua e confiável. Além disso, são analisados os benefícios associados, incluindo a redução da dependência de combustíveis fósseis e a diminuição das emissões de gases de efeito estufa. Contudo, também são abordados os riscos envolvidos, como a gestão de resíduos radioativos e o potencial para acidentes nucleares. Assim, observa-se uma ponderação acerca das qualidades e eventuais

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riscos dessa alternativa, possibilitando a implementação de estratégias para assegurar a segurança energética no sistema elétrico brasileiro.

Palavras-chave: Energia Nuclear. Sistema Elétrico. Diversificação Energética. Emissões de Carbono.

RESUMEN

El presente artículo explora la energía nuclear en el contexto del sistema eléctrico brasileño, iniciando con un panorama global que destaca la importancia de esta fuente energética en la matriz eléctrica mundial, subrayando su papel crucial en la diversificación de las fuentes de energía y en la mitigación de las emisiones de carbono. El estudio también examina esta visión global y la situación específica de Brasil, donde la contribución de la energía nuclear aún es modesta. Además, se constatan las cualidades inherentes a esta fuente, como su densidad energética y la capacidad de proporcionar una energía continua y confiable. Asimismo, se analizan los beneficios asociados, incluyendo la reducción de la dependencia de combustibles fósiles y la disminución de las emisiones de gases de efecto invernadero. No obstante, también se abordan los riesgos involucrados, como la gestión de residuos radiactivos y el potencial de accidentes nucleares. De este modo, se observa una ponderación acerca de las cualidades y los eventuales riesgos de esta alternativa, possibilitando la implementación de estrategias para garantizar la seguridad energética en el sistema eléctrico brasileño.

Palabras clave: Energía Nuclear. Sistema Elétrico. Diversificación Energética. Emisiones de Carbono.

1 INTRODUCTION

The history of nuclear energy, according to Passos *et al.* (2011) is intrinsically linked to the development of humanity, as the philosophers of Ancient Greece were pioneers in formulating the idea that matter is made up of atoms. Not only relevant names such as Marie and Pierre Curie and leading advances that made the understanding and application of this energy source possible. However, it was not until the 1930s that scientists observed the potential of nuclear fission, paving the way for numerous transformations and advances. Nevertheless, the Manhattan Project corroborated significantly, since it aimed to obtain the nuclear bomb and, due to this, intensive investments were made to achieve this objective. This organization had great names in science, such as Enrico Fermi and Niels Bohr, and was led by Robert Oppenheimer, popularly known as the "father of the atomic bomb".

Nuclear energy, according to Eletronuclear (2024), consists of a form of energy derived from the atomic nucleus, being characterized by the release of a significant amount of energy during nuclear processes and presents nuclear fission and nuclear fusion as its main phenomena. Nuclear fission is based on splitting the nucleus of an atom into smaller fragments releasing energy. Nuclear fusion, on the other hand, is based on the combination of two nuclei and, consequently, on the release of energy.

For the generation of nuclear energy, according to the Nuclear Energy portal (2024), specific raw materials are used, especially the radioactive isotope uranium-235. Uranium-235 is crucial in nuclear fission processes in nuclear reactors, as it has a high susceptibility to fission and therefore results in the release of energy. Also, to ensure an efficient procedure, it is necessary to enrich uranium to increase the concentration index of the isotope uranium-235, since, under natural conditions, only a small portion of this element is composed of this isotope.

Today, that is, nowadays, the use of this energy source as an alternative worldwide, since global warming puts pressure on the use of fossil fuels and, for these reasons, the nuclear source is an interesting option, as Gomes (2017) elucidates. Undoubtedly, this source plays a strategic role in the global panorama, providing an energy component that can meet world demand in an efficient and sustainable way. Together, the diversification of energy sources is crucial to reduce dependence on fossil fuels and contribute to energy security. Likewise, it provides an increase in energy security by reducing the country's vulnerability to fluctuations in fuel prices and supply interruptions. Therefore, safe production is essential for energy autonomy, positively impacting the economy and, for this, it is imperative to achieve strict standards of waste management and safety.

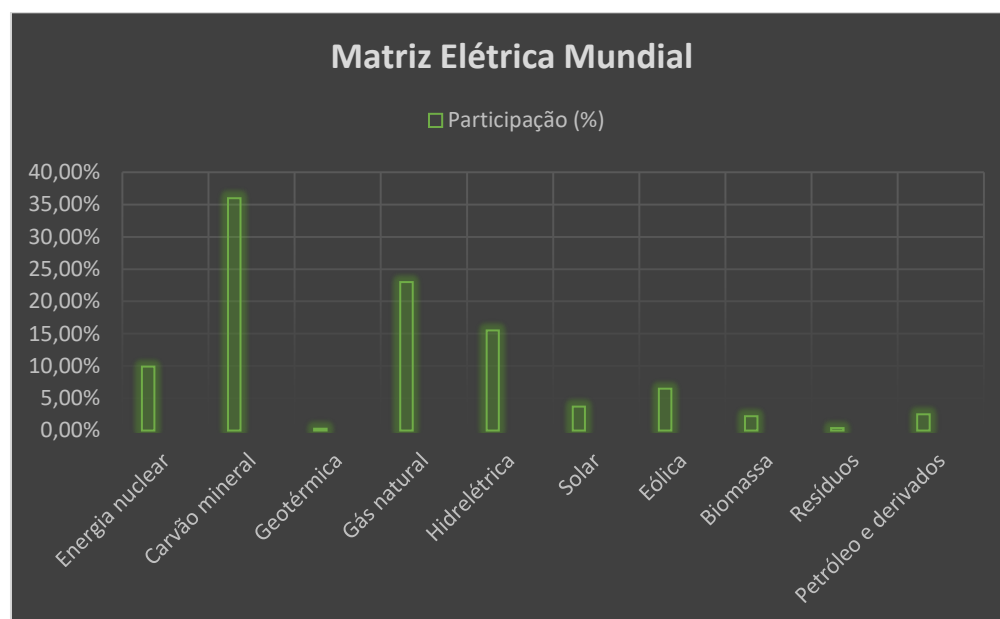
2 GLOBAL OVERVIEW

This aspect plays a fundamental role in the global energy landscape, being an indispensable source for many countries. Currently, the world has a diversified electricity matrix and, according to EPE (2023), it is mostly composed of mineral coal and natural gas. Therefore, Figure 1 shows the substantial participation of fossil fuels and the complementarity of renewable sources such as solar, wind, hydroelectric and the significant contribution of nuclear sources.

Furthermore, as mentioned earlier, nuclear energy is indispensable for some countries, making them significantly dependent on this source. In this way, it is feasible to observe the energy situation in France, where this source represents 70% of the generation capacity, as presented by Bhutada (2022). In addition, this energy source accounted for 2,553 TWh of global energy production, led by the United States of America (30.9%), China (13.5%) and France (13.3%).

Figure 1

World Electricity Matrix



Source: The authors.

Not only that, it is a feasible alternative for the reduction of fossil fuels that are aggressive to the environment and, in addition, certain countries have a greater allocation to nuclear energy due to issues such as high energy efficiency and geoFigureical aspects. Thus, the relevance of this supply alternative is reiterated, since nations such as France, Slovakia and Ukraine have, respectively, 70.6%, 53.1%, and 51.2% of their energy matrix in this source. However, still cited by Bhutada (2022), there are 448 nuclear reactors in operation in the world, 96 in the USA, 58

in France, and 50 in China. Moreover, the prospect is for expansion, since China plans to invest 440 billion dollars to build 150 new reactors by 2035.

3 NUCLEAR ENERGY IN BRAZIL

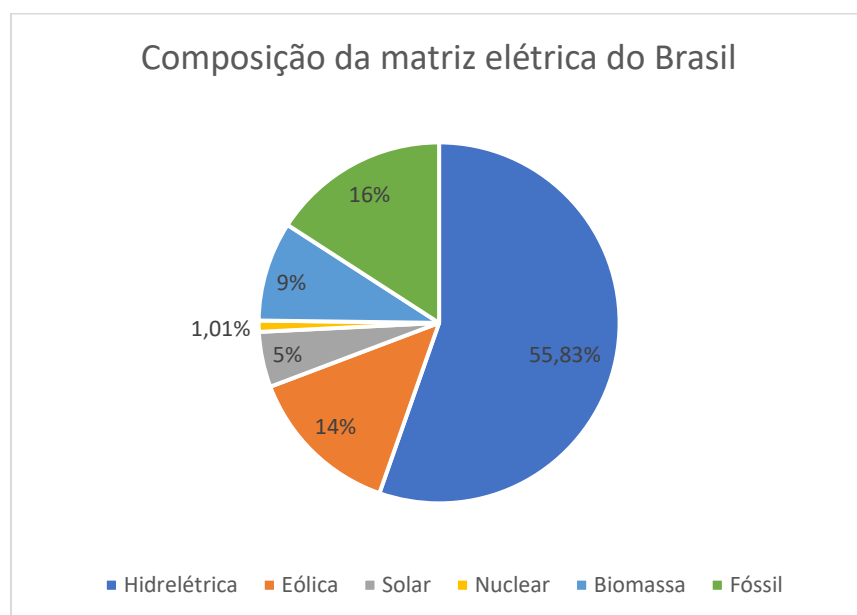
Historically, the Brazilian electricity matrix is diversified and considerably clean, with a tendency to become increasingly renewable, causing wind and solar energy to gain greater share. In addition, Montalvão (2012), the renewable profile guarantees low tariffs and energy security, considering that these sources are inexhaustible. As a result, Brazil has the largest electricity system in Latin America and, consequently, is among the ten largest electricity producers on the planet.

Currently, the matrix consists of various energy sources, such as hydroelectric, wind, thermal, nuclear, photovoltaic and biomass, as illustrated in Figure 2. In addition to this factor, according to Guimarães (2016), it is observed that nuclear energy is a fundamental part of the resolution of the national hydrothermal energy transition. Moreover, it is possible to analyze the fundamental link between energy availability and consumption with the degree of economic development of the country, since such factors are directly proportional. Therefore, in view of the growing energy demand, it is necessary to increase national generation to meet this problem and, due to this, nuclear energy is viable in view of its generational predictability.

In addition, Brazil is one of the countries that has a wide domain over the uranium enrichment cycle and, at the same time, has reserves in its territory. Allied to this, as previously mentioned, the diversification of the electricity matrix ensures a low tariff and, if such a scenario did not occur, Brazil would present a significant increase in tariffs and local industries would lose competitiveness in the international market. Nevertheless, as stated in the National Energy Balance 2024 (2024), nuclear energy represents 1.2% of the entire Domestic Energy Supply (OIE), being generated through the Angra 1 (illustrated in Figure 3) and Angra 2 plants, in addition to the Angra 3 construction project being in progress.

Figure 2

Composition of the Brazilian electricity matrix



Source: The authors.

Figure 3

Angra dos Reis nuclear power plant (RJ)



Source: NS Energy

3.1 REGULATORY BODIES

In addition, in the Brazilian electricity sector, there are several regulatory bodies and entities that manage the competent aspects of nuclear energy, however, the following stand out:

- National Nuclear Energy Commission (CNEN): It is responsible for the aspects of nuclear safety, radiological protection and regulation of nuclear activities in the country. Thus, it licenses and inspects nuclear installations, in order to ensure that the operation complies with safety standards;
- National Electric Energy Agency (ANEEL): Its objective is to regulate and supervise the production, transmission, distribution and commercialization of electricity in Brazil;
- National Electric System Operator (ONS): Seeks to coordinate and control the operation of electricity generation and transmission in the SIN (National Interconnected System);
- Ministry of Mines and Energy (MME): Coordinates the country's energy policy and defines the guidelines for the development of the nuclear sector, in line with safety and sustainable development policies.

4 ENERGY EFFICIENCY

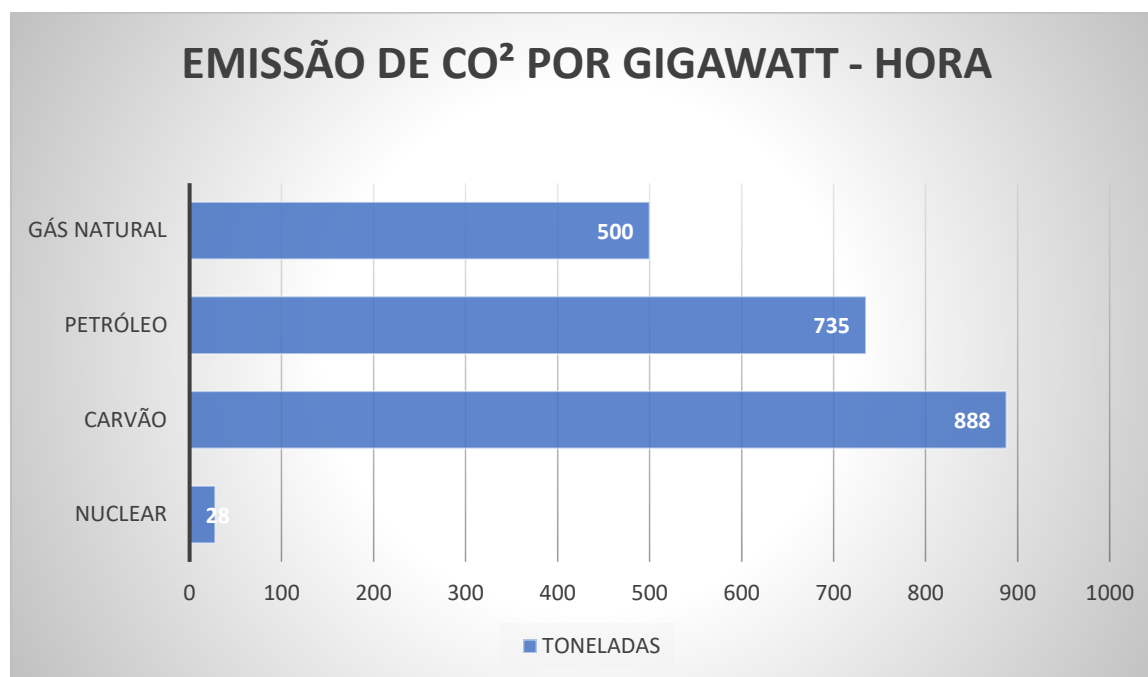
The demand for uranium comes from nuclear power plants, consequently, it is the companies that use this element as fuel for their reactors and, on the other hand, the *players* that supply this raw material are the mining companies. In addition, it is noted that the superiority of uranium as an energy source occurs as a result of the level of energy density, one of the main competitive advantages of this alternative. Likewise, Conte (2021) illustrates energy efficiency through a proportionality, where a uranium pellet (about 1 centimeter high and in diameter, with the height being greater than the diameter), is equivalent to 120 gallons of oil, 17,000 cubic feet of natural gas or 1 ton of coal, thus evidencing the high density of the material and, as a result, your generational capacity. However, it is noted that the competitive advantages of this source stimulate its use in the context of energy transition.

In addition, the energy density of uranium is one of the main causes of the increase in demand, since it allows the storage of substantial amounts of the material in a logistics warehouse. In this way, according to Bhutada (2021), it becomes the only energy source capable of being stored under these conditions, corroborating energy security and enabling exponential production from a tiny amount of raw material. Therefore, as Bhutada (2021) explains, due to the high density levels of uranium, it requires, on average, 75 times less space than the photovoltaic alternative and 360 times less land than the wind option. In addition, the relative availability of the material is a fundamental factor in its viability, as it is 37 times more abundant than silver and 700 times more present than gold (Bhutada, 2021).

However, the sustainable aspects of the energy of atomic nuclei are another competitive advantage that this alternative has, especially with regard to CO² emission per Gigawatt hour. Thus, it is observed in Figure 4 the favorable scenario in relation to nuclear energy in view of this issue. (BBC News, 2022).

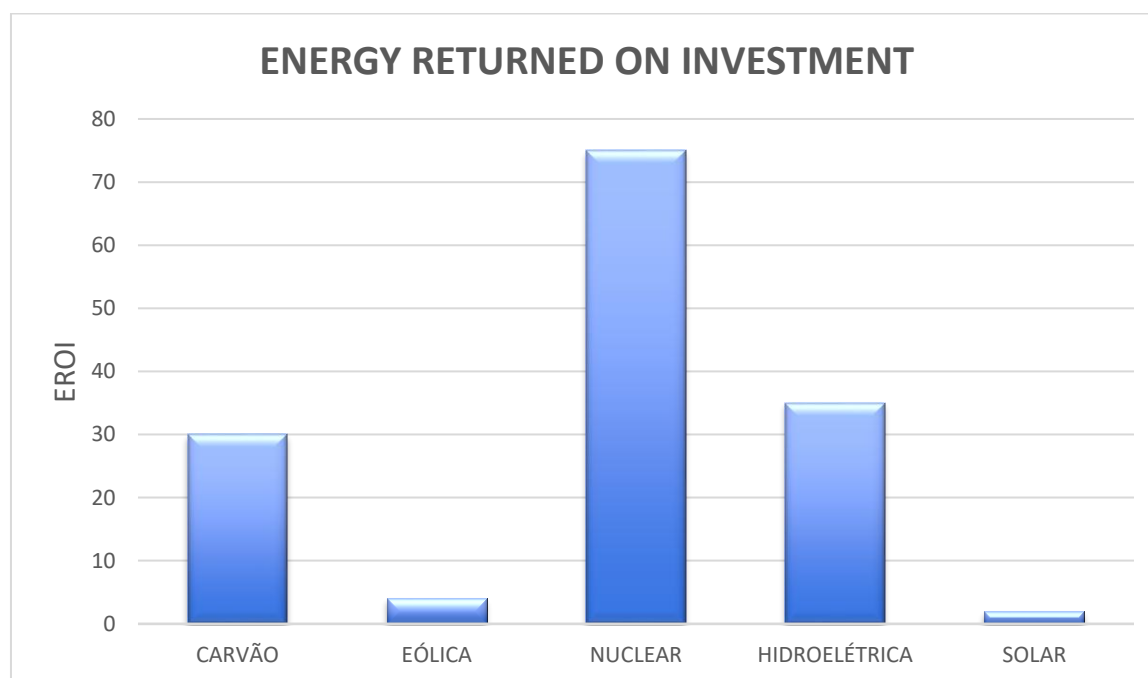
Figure 3

CO² emission per Gigawatt - Hour



Source: Prepared by the authors.

Additionally, according to the *Corporate Finance Institute* (2024), *Energy Return On Investment*, abbreviated as *EROI*, is a financial indicator that illustrates energy efficiency, as it consists of the ratio between the amount of energy generated by a source and the amount used to obtain this resource. Therefore, it is noted that any number equal to 1 represents the equilibrium point, while values greater than 1 consist of a positive balance. However, as shown by the *Corporate Finance Institute* (2024) and illustrated in Figure 5, the *EROI* that nuclear energy presents is substantially higher than its peers, and is therefore a competitive advantage.

Figure 5*Energy Returned On Investment*

Source: Prepared by the authors.

5 BENEFITS

This type of energy, as well as others, has positive and negative points, however, it is necessary to weigh these aspects rationally to verify its feasibility of implementation. However, nuclear energy has some substantial competitive, economic and strategic advantages and, due to this, it becomes attractive for implementation in certain conjunctures and needs.

A priori, nuclear energy is of great importance to ensure the security of energy supply due to high predictability, generational constancy, storage capacity and independence from climatic factors. Not only that, the expressive density of the material used allows the production of high amounts of electricity through a small amount of raw material and, therefore, as previously discussed, the substantial energy efficiency of this source is noted. Furthermore, according to Montalvão (2012), the use of this source does not emit greenhouse gases, promotes a low release of waste and does not require a significant area for the construction of the plant in relation to other alternatives. In other words, it is possible to analyze the rigidity of the procedures related to the safety of the facilities and the intense process of continuous improvement of them, causing the plants to demonstrate considerable increases in the levels of protection.

In addition, it promotes the diversification of the energy matrix, corroborating the transition movement of this sector. Thus, it is observed that the use of various generational sources is a strategic objective of extreme relevance for numerous countries, since it ensures geopolitical

advantages, increases energy security, reduces vulnerability to fluctuations in international prices and possible interruptions in supply. Therefore, with assertive investment and development policies, nuclear energy can expand its relevance and solidify the national electricity system (Plum, 2024).

Likewise, it contributes significantly to technological development and scientific innovation, as the sector is marked by constant advances in areas such as nuclear physics, engineering, and safety measures and procedures. Therefore, such evolutions are not restricted only to the energy industry, but also have applicability in other fields, such as agriculture through food irradiation techniques, and in medicine, through radiotherapy and other diagnostic imaging. In addition to this factor, Tang (2008) emphasizes that the use of capital destined to investments in energy strengthens the energy infrastructure, promotes scientific and technological progress, positively impacting society.

6 RISKS

The nuclear source has substantial positive aspects; However, it also has negative conjunctures. Among the most well-known risks, those of an economic, physical and strategic nature are observed. At the same time, according to Goldemberg (2008), other energy modalities also employ risks, but not on the same scale as nuclear energy. Consequently, with the nuclear source, the associated problems acquire greater expressiveness.

Economic risks refer to the resources allocated to security and their necessary procedures, which, consequently, reflect on the increase in cost, making it difficult to structure projects to finance these investments. However, bureaucracy and public opposition can cause delays in reactor construction, leading to increased capital expenditure (a type of resources set aside for the purchase of goods to increase production, also known as *CAPEX*) and incurring interest.

In addition, strategic risks, as highlighted by Goldemberg (2008), refer to the geopolitical implications arising from the possession of a nuclear device and, potentially, the allocation of resources for war purposes. As a result, treaties and agreements for nuclear non-proliferation were established, since this issue was the trigger for certain conflicts. In addition, the risk inherent in the acceptance of public opinion is an important factor that must be weighed in decision-making, since there are strong anti-nuclear movements in Brazil and in the world. In addition, the existence of geopolitical risk through military incursions is verified, see the existing situation in Niger and its possible impact on the country's nuclear activity.

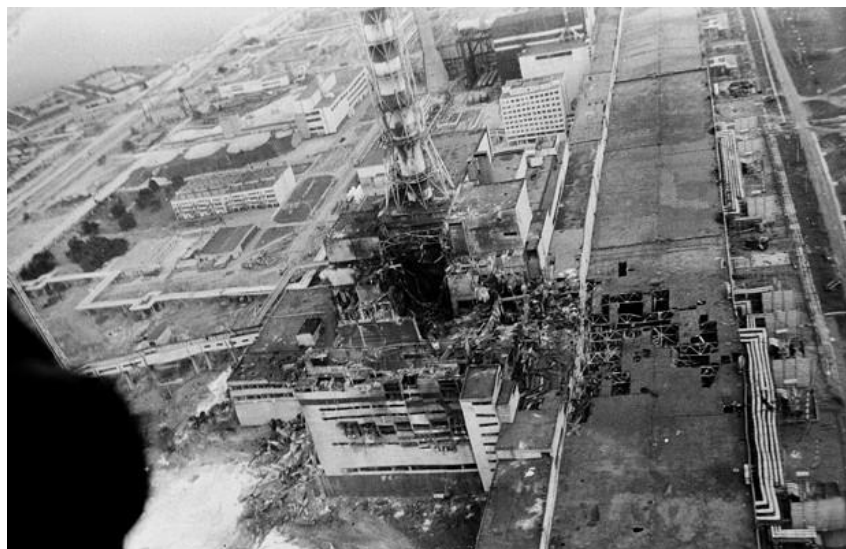
In fact, the physical risks consist of possible structural insecurity related to nuclear leaks and explosions. By the way, the concern with the disposal of the material used is latent, since there is no appropriate environment to deposit this material to this day. Likewise, the emblematic episodes of nuclear accidents elucidate the potential danger that these plants, if not managed and built in the right way, can bring. In other words, human history has faced 3 major nuclear tragedies, Chernobyl, Fukushima and Three Mile Island.

Nevertheless, the public acceptance of nuclear power plants, mainly due to the lack of knowledge on the subject, is a factor that should be considered in the analysis of implementation, even if it does not represent impediments in many countries. However, according to Guimarães (2016), the biggest obstacle is the high CAPEX and the difficulties of designing projects to make these long-term investments viable.

First, the Chernobyl incident, explained in Figure 6, happened on April 26, 1986, when the technical team in charge of analyzing the operation of the reactor did not comply with the safety regulations and, in view of the plant's obsolete technology, the reactor showed significant instability and, consequently, affected the explosion of reactor 4. In addition, according to Montalvão (2012), Chernobyl occurred due to a combination of three aspects: government irresponsibility, human error, and outdated technology.

Figure 6

Chernobyl power plant, damaged after the explosion, in a photo from May 1986



Source: G1

In addition, the occurrence of Three Mile Island dated 1979 and shown in Figure 7 was caused by an operational mistake and failure in an equipment. At the same time, the lack of

preventive maintenance and poor qualification of professionals demonstrate the negligence of those responsible in a situation that released a substantial amount of radioactive liquid (water) into a river in the state of Pennsylvania.

Figure 7

Aerial view of the Three Mile Island nuclear power plant near Harrisburg, Pennsylvania, the scene of a nuclear accident



Source: WTOP News

Subsequently, the accident in Fukushima, observed in Figure 8, in which radioactive water leaked into the sea and emitted radioactive gas into the atmosphere, was caused by poor design and planning of the plant's infrastructure. Due to the tsunami that devastated Japan, structural deficiencies came to light and caused severe damage.

Figure 4

Aerial view of the Fukushima nuclear power plant after the explosion



Source: Daily Mail

In addition to the factors explained above, radioactive waste is substantially dangerous to society, since it consists of all waste material that is made up of radioactive chemical compounds. Such waste is obtained from hospitals and nuclear power plants and, in addition, endangers not only human beings, but also nature. As a result, the proper disposal of this content is essential to prevent impacts. Therefore, material with low or medium levels of radioactivity is deposited in underground facilities, commonly in power plants. In addition, high-risk substances are treated through management and confinement for significant periods due to their durability. In addition, in view of the risk aspects discussed above, Eletronuclear (2024) emphasizes the importance of the correct adoption of safety procedures and the constant evolution of nuclear technology, minimizing possibly harmful particularities and corroborating the diffusion of the use of this energy source.

7 CONCLUSIONS

For all that has been exposed throughout this work, the presence and relevance of nuclear energy both in the world electricity matrix and in the Brazilian scenario is evident, thus verifying the strategic role it plays in the diversification of energy sources and in the mitigation of carbon emissions. Not only that, the nuclear source proves to be viable and beneficial, since it presents expressive energy density indexes and corroborates with the increase in predictability in energy generation, acting as an interesting alternative to complement the use of other options.

Above all, in addition to the high efficiency rates, this energy source also has the benefits of high storage capacity, expressive durability and exponentially rigorous safety processes that

contribute to its credibility. In addition, it is imperative to highlight the risks existing in the operation, especially those of a physical, economic and strategic nature that strongly oppose the positive aspects, making it necessary to have a rational consideration to make a decision. Moreover, economic risks are linked to the intensive need for investments to finance these projects, while strategic risks represent the geopolitical issues inherent to the activity. Therefore, physical risks consist of the possibility of an operational failure or accident occurring. Thus, it is noted that even with the existing risks, the qualities of nuclear energy stand out as the demand for energy security and independence grows.

In addition, the high level of acceptance of the population living in areas close to the reactors is reiterated, in addition to positive socioeconomic impacts through the qualified labor and jobs offered. In addition, the strict safety and *compliance* procedures corroborate to expand the use of this energy. Thus, due to the current situation of energy transition and urgency in reducing carbon emissions, nuclear energy behaves as a fundamental alternative for solving the energy supply deficit, as it has substantially higher efficiency rates than other alternatives, in addition to requiring smaller amounts of the land production factor and having the highest EROI. In view of the above, it is found that the nuclear alternative is viable to solve the Brazilian energy problems, since even though it still has a limited participation in the national electricity matrix, the potential and need for growth is remarkable. With this, it is interesting to spend more investments to promote the evolution of the sector and contribute to the assertive realization of the energy transition, obtaining a safe and more capable electricity matrix to supply the existing deficit.

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