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Environmental costs of nuclear reactors: a literature review

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Abstract: The provision of reliable and affordable energy, while reducing environmental impacts, is an increasing challenge. Nuclear energy stands out as an important low-carbon alternative in the energy transition, supporting intermittent renewable sources. However, despite its environmental advantages, nuclear energy still faces some challenges, such as the decommissioning of reactors at the end of their life cycle and technological advancements with the construction of Small Modular Reactors (SMRs). The costs and environmental impacts of these processes must be considered to inform energy decision-making. The objective of this article is, therefore, to present a literature review on the calculation of environmental costs in the nuclear energy sector. This article marks the initial stage of an ongoing research project aimed at creating a program to calculate the environmental costs of Brazilian nuclear power plants and future SMRs. Thus, this study was conducted as qualitative research through a literature review, as part of an ongoing project. The literature review highlighted the theoretical basis that involves the subject, as well as the projects and studies already carried out on the topic. Finally, the calculation of environmental costs is encouraged, with the ultimate purpose of supporting energy decision-making.

Keywords: environmental cost, nuclear energy, SMR, energy decisions.

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Custos ambientais de reatores nucleares: uma revisão da literatura

Resumo: O fornecimento de energia confiável e acessível, com a redução dos impactos ambientais, é um desafio crescente. A energia nuclear se destaca como uma importante alternativa de baixo carbono na transição energética, apoiando fontes renováveis intermitentes. Entretanto, apesar de suas vantagens ambientais, a energia nuclear ainda enfrenta alguns desafios, como a desativação de reatores ao atingirem sua vida útil e o avanço tecnológico com a construção dos Small Modular Reactors (SMRs). Os custos e impactos ambientais desses processos devem ser considerados para embasar as tomadas de decisões energéticas. O objetivo deste artigo é, portanto, apresentar a revisão bibliográfica sobre o cálculo de custos ambientais no setor de energia nuclear. Este artigo marca a etapa inicial de um projeto de pesquisa em desenvolvimento que visa criar um programa para calcular os custos ambientais das usinas nucleares brasileiras e futuros SMRs. Assim, este estudo foi conduzido como uma pesquisa qualitativa por meio de uma revisão da literatura, como parte de um projeto em andamento. A revisão da literatura destacou a base teórica que envolve o assunto, bem como os projetos e estudos já realizados sobre o tema. Por fim, o cálculo de custos ambientais é incentivado, com o propósito final de auxiliar na tomada de decisões energéticas.

Palavras-chave: custo ambiental, energia nuclear, SMR, decisões energéticas.

1. INTRODUCTION

The provision of reliable and affordable energy for a growing population, while seeking to reduce environmental impacts, becomes a challenge. To assess the feasibility of the various available energy sources, it is necessary to consider price, availability, and their environmental impacts [1].

Although no source is entirely free of emissions, nuclear energy can be considered an energy alternative, primarily because it is a low-carbon energy source. Furthermore, in a scenario of energy transition, nuclear energy is an option to offset the variability of supply from alternative sources, such as wind and solar [2].

The future of nuclear energy includes the decommissioning of operational reactors that reach the end of their life cycle, as well as technological prospects with the consolidation of third and fourth generation reactors, particularly the construction of Small Modular Reactors (SMRs) [3]. Thus, the costs related to these procedures, including their associated environmental impacts, must be considered when presenting nuclear energy as a viable alternative in an energy transition.

The costs of environmental impacts are generally referred to in the literature as external costs, environmental costs, or externalities, and their pricing allows the environment to no longer be an unlimited and free resource. The inclusion of such costs aids in preservation tools and decision-making at a sustainable level [4].

Thus, for a comprehensive analysis of the feasibility of nuclear energy within the parameters of sustainability, it is necessary to consider the environmental costs involved in all phases of the nuclear power plants' life cycle, including the implementation, operation, and decommissioning phases.

1.1. Objectives and motivations

The objective of this article is to study the importance of calculating the environmental costs of electricity generation sources, and more specifically nuclear energy, through a literature review. This work is part of an ongoing research project, which has the ultimate goal of developing a program for calculating the environmental costs of Brazilian nuclear power plants and future SMRs.

The motivation for this project arose from the need for a comprehensive evaluation of the environmental costs arising from nuclear power plants. A complete analysis, considering the implementation and decommissioning phases, can support nuclear energy as a viable alternative, within the parameters of sustainability, to meet the new demands generated for the electric sector in Brazil and worldwide.

Although the calculation methodology for quantifying the costs of the implementation and decommissioning phases and an accessible tool for such calculation are being developed, the literature review is fundamental for the development of this project.

2. MATERIALS AND METHODS

This work is a qualitative research project, developed through a literature review. Comprehensive searches were conducted for articles, reports, theses, and dissertations in the main databases and research tools available. The search strategy involved the use of specific keywords related to nuclear energy, environmental costs, and life cycle assessment. The selection criteria were based on relevance, publication date, and the credibility of the sources. The collected information was synthesized and analyzed to provide a detailed overview of the theoretical foundation of the topic, the methodologies used by completed projects, and the most current findings in the field, with the aim of identifying gaps and proposing future research directions.

3. RESULTS AND DISCUSSIONS

In this topic, a literature review is presented to organize existing knowledge on the measurement of environmental costs in the nuclear industry. This review provides a solid theoretical foundation, highlighting key concepts and theories pertinent to the subject. Furthermore, it examines previous studies and projects that have focused on evaluating these costs, outlining the methodologies adopted and the conclusions drawn. By structuring the literature review in this manner, the goal was to establish a robust foundation to support the ongoing research project.

3.1. Theoretical Framework

The use of resources for electricity production, although indispensable in the contemporary world, generates social and environmental costs such as effects on public health, air, water, and soil pollution, ecological disturbances, species loss, and land use. The costs of these damages are commonly referred to in the literature as external costs, environmental costs, or externalities [5].

To study the relationship between economic activity and the natural environment, economics provides analytical tools aimed at understanding these interactions, their implications, and identifying opportunities for solutions [6].

A frequently employed economic concept in this context is externality, referring to an effect stemming from a market transaction that influences a third party not directly involved in the transaction itself. If this effect results in costs, it is termed a negative externality; conversely, if it yields benefits, it is termed a positive externality. Pollution, therefore, exemplifies a negative externality in economic terms. [6].

In this case, the objective is to identify and monetize external costs. However, it is often challenging to assign monetary values to these costs. If not quantified, the market typically assigns a value of zero automatically, as these costs do not directly influence

consumer and producer decisions. Therefore, in addition to the marginal costs of producing a good or service, it is crucial to also consider the costs of negative externalities—specifically, environmental costs—as a means of accounting for environmental impacts that need to be taken into account when analyzing the overall social welfare of a market [1], [6].

The literature on this topic further emphasizes the importance of environmental valuation, focusing on four arguments: environmental services are not free; valuation leads to more rational and informed decision-making; something without a price does not imply it has infinite value; and finally, it is relevant in an economic system that allocates resources based on consumer preferences [7].

As these preferences need to be quantified, money becomes the primary measure. Therefore, integrating environmental costs into decision-making allows for weighing the advantages and disadvantages of an action based on a single measure of benefits and costs: money.

It is important to note that economics is an applied social science, not an exact science, as it studies societal behaviors. Therefore, the interpretation of values should be approached with caution [7]. Furthermore, environmental issues involve interdisciplinary approaches, requiring the study of various fields of knowledge for their resolution. However, it is essential to acknowledge the limits of scientific uncertainty that extend beyond economics [8]. Nonetheless, economic valuation provides a crucial perspective for more efficient environmental protection and serves as an important tool for decision-making.

Valuation methods can be classified into direct and indirect techniques. Direct techniques aim to measure the monetary value of environmental impacts directly, either through a substitute market or experimental methods. On the other hand, indirect techniques seek to calculate the "dose-response" relationships between pollution and effects, such as on health [7].

There is no consensus in the literature regarding classification; however, various studies on the topic aim to present different methods and discuss their advantages and disadvantages. The main challenge of valuation techniques lies in assessing the reliability of

results, given that there is no absolute correct parameter or real market to serve as a reference. To address this, reliability needs to be tested and compared across similar contexts, with other techniques, and against market experiences [7], [8].

To provide a solid foundation for this study, a literature review of previous research, particularly within the electricity generation sector, is essential and presented below.

3.2. Previous Works and Projects

The literature review identified environmental valuation studies across various sectors of the economy. However, the following section will focus on the primary references of projects and research related to the energy sector. While some of these studies may not exclusively focus on nuclear energy, their methodologies and findings provide valuable insights into understanding the studied scenario.

Two types of studies were observed: those that quantitatively calculated the monetary costs of environmental effects, and those that identified the environmental impacts of energy sources. For the development of this work, both approaches were considered relevant as sources of reference and justification.

It has been observed that studies on the environmental impacts and external costs of electricity generation have been developed since the early 1990s. In this context, the ExternE project emerged as an acronym for "External Costs of Energy," initiated by the European Commission to assess externalities associated with electricity generation. This project produced a series of reports from 1991 to 2005, focusing on fossil, nuclear, and renewable sources. The methodology developed utilized the bottom-up approach, also known in the literature as the Impact Pathway Approach (IPA). This approach involves assessing impacts in monetary terms based on specific local data, technology studied, characteristics of pollutant receptors, and their dose-response functions [9].

One of the reports in the ExternE project series illustrates the application of methodology across the eight stages of the nuclear fuel cycle in France. For the electricity generation phase, a 900 MW(e) Pressurized Water Reactor (PWR) served as the reference. The monetary valuation of human health impacts resulted in an estimated total cost of 0.47 mECU/kWh, without applying any discount rate. Within this total, operational costs accounted for 89%, construction costs for 7%, and decommissioning costs for 4% [10]. All monetary values in the ExternE project were originally presented in ECU, the precursor currency to the Euro, which had an average value of 0.77 USD in 1995 [11].

Based on the methodologies developed by the ExternE project, numerous studies have been published in various countries and contexts, establishing it as a primary reference for valuation methods in the energy sector. However, the literature review reveals that many studies simplify these methodologies, primarily focusing on valuing human health impacts from particulate matter emissions and climate change impacts from greenhouse gas emissions into the atmosphere. In these cases, nuclear power plants typically show negligible environmental costs since they do not produce significant greenhouse gases during electricity generation [12].

Nevertheless, for a more precise estimate of external costs, some authors argue that health damages caused by the emission of radionuclides during electricity production should be considered. This was the case in a study conducted to compare major electricity generation technologies in Lithuania. The environmental costs per kWh of electricity produced were calculated by multiplying the marginal value per unit of emission by the quantity of pollutants emitted in each production stage. The results indicated hydropower and wind power had the lowest external costs. Nuclear power plants showed lower external costs compared to all fossil fuel-based technologies but higher than renewable energy technologies, except for biomass-based technologies [13].

Similarly, in 2008, a study conducted an economic assessment comparing nuclear reactors to conventional fossil fuel power plants such as coal, gas, and oil. The findings

showed that nuclear systems are affected by 5 to 10% due to internalizing environmental costs. Drawing from ExternE project reports, the authors compared damage costs per kWh for various energy generation technologies. The results varied depending on the plant's location. Despite this variability, wind energy emerged with the most favorable results, closely followed by nuclear energy [5].

Although there are few studies specifically developed for the nuclear sector, the International Atomic Energy Agency (IAEA) has developed the SIMPACTS tool (Simplified Approach for Estimating Impacts of Electricity Generation). This tool employs a methodological approach similar to the ExternE project, with necessary simplifications, and utilizes dose-response data and studies presented in the project's reports. The program is notable for its simplicity and requires a reduced number of input data [14].

The SIMPACTS program, in its initial version, was used to assess the environmental impacts of electricity generation in Indonesia. Comparing two coal-fired plants, two natural gas plants, and one nuclear plant resulted in lower costs for the nuclear source, followed closely by the natural gas plants [10].

In Brazil, the environmental costs associated with electricity generation from hydroelectric and natural gas thermal power plants were calculated in 2001. After an extensive study of methodologies for environmental valuation and the impacts generated by these sources from plant construction onwards, the author proposed a different method for each identified impact. Despite its more qualitative focus on source comparison, a case study was conducted to value the externalities generated. The author faced significant challenges in obtaining reliable data, especially national data, to establish dose-response functions and other environmental monitoring and occupational accident-related data [15].

Specifically for nuclear power, the calculation of environmental costs associated with electricity generation was conducted for the Angra 1, 2, and 3 nuclear power plants using the SIMPACTS program (2006 version). The results were compared with data from the

Balakovo reactor in Russia, the Serra da Mesa hydroelectric plant in Brazil, and a generic coal-fired plant in France, all with the same generation capacity as provided in the program. Based on the calculations, nuclear reactors showed lower environmental costs compared to the other sources analyzed [16].

In a more recent study, the aim was to identify the environmental externalities associated with atmospheric emissions from alternative sources of electricity generation in Brazil, specifically focusing on the generation stage. The results obtained aligned with expectations, showing higher environmental costs for technologies with more significant atmospheric emissions. Based on these findings, it was concluded that internalizing environmental costs would represent approximately 10% of the energy price for residential consumers. In this study, nuclear power generation was treated as having negligible emissions of major atmospheric pollutants, and emissions of radionuclides during normal operation were considered insignificant for the calculations, thus resulting in zero environmental costs [17].

The following studies stand out, as they analyze the environmental impacts of energy generation sources, even though their main objective is not to assess environmental costs. They serve as important references for developing the methodology proposed in this project, particularly concerning the identification of environmental impacts during the construction and decommissioning phases separately.

These studies mostly employ a Life Cycle Assessment (LCA) approach. LCA aims to quantify the potential environmental impacts arising from the manufacture and use of a product or service. Its systemic approach is known as "cradle-to-grave," as it involves collecting data across all stages of the studied object's lifecycle, from raw material extraction through production, distribution, consumption, and final disposal [18]

In 2002, a study was conducted in South Korea with the aim of evaluating and estimating the environmental impacts of nuclear fuel cycles to support energy policy decision-making for sustainable development. Life Cycle Assessment (LCA) was used as the

tool for this purpose. The results showed that the methodology allows for comparative assessments of both radiological and non-radiological aspects, aiming to build an environmental database to objectively demonstrate the environmental predominance of nuclear energy over other energy sources. The authors also highlighted the challenges in interpreting and quantitatively comparing environmental impacts across different categories, emphasizing the importance of standardization and weighting [19].

In 2007, an article evaluated Greenhouse Gas Emissions (GHG), comparing solar and nuclear sources, through a review of studies using LCA. They concluded that emissions from both sources are comparable, with no clear advantages for either. Additionally, they highlighted the impact of the construction phase of nuclear plants, which requires a large amount of materials due to their size, such as concrete, steel, copper, aluminum, and diesel for machinery operation. Regarding decommissioning, they emphasized the generation of radioactive waste, especially high-activity waste like used fuel and fuel rods. Concerning GHG emissions, the focus of the study, during these phases, they found that data available in the literature varied depending on the methodology used, particularly for decommissioning, for which real data did not yet exist at the time. According to the data obtained, emission estimates range from 0.5 g CO_2-eq/kWh to 34 g CO_2-eq/kWh for the construction and decommissioning phases of nuclear plants [20].

In 2009, the same authors conducted a literature review aiming to assess land use in electricity generation cycles, both for conventional and renewable energy sources. The results indicate that biomass demands the largest land area, followed by the nuclear fuel cycle in terms of land use. The authors point out that nuclear power plants also have a high demand for land due to requirements such as exclusion zones and safety barriers for potential accidents. However, when land use is normalized relative to energy production over a 30-year period, nuclear energy shows more favorable results. Nonetheless, the authors highlight

solar energy as an option with lower environmental impact, as it does not cause disruptions from fuel extraction [21].

In Brazil, a study aimed to assess the contribution of nuclear energy to the sustainable diversification of the Brazilian electricity sector, considering social, environmental, and economic criteria through quantitative comparisons with other sources. The results indicate that nuclear energy has low GHG emissions throughout its energy chain. In terms of natural resource use, it occupies an intermediate position, but its impact can be mitigated with proper management of radioactive waste. Socially, despite incidents like Three Mile Island (1979) and Chernobyl (1986), nuclear energy has a global impact below the average. From an economic standpoint, its competitiveness is close to sources like coal, biomass, and natural gas, albeit with relatively higher costs. However, factors such as geopolitics and public acceptance were not addressed in this study [22].

A more qualitative article aimed to compare the environmental impacts of various low-carbon alternative energy sources such as hydro, solar, wind, biomass, and nuclear. This comparison was based on a literature review that assessed material and energy requirements, health effects, accident risks, and public opinion. Despite nuclear energy showing clear advantages in several categories, especially when normalized for electricity generated, public opinion remains opposed to it. This reinforced the conclusion that there is no ideal energy generation system in all aspects, as each presents benefits and challenges. The article highlighted the need for a combined approach and emphasized the importance of life cycle assessments in comparing these sources [23].

Also through the life cycle approach, an analysis and comparison of the environmental impacts of nuclear, wind, and hydroelectric sources in Canada was conducted. This included calculating greenhouse gas emissions during each phase of the plants, including construction and decommissioning. It was concluded that for the nuclear energy scenario, the decommissioning phase was the main contributor to environmental impacts. However, they

emphasized that the analysis of environmental impacts becomes incomplete when only considering GHG emissions [24].

Specifically for SMRs, a LCA study was conducted on an open nuclear fuel cycle in the United States, focusing on the NuScale reactor as it is the most advanced in the U.S. licensing process. The study considered the production of 3.6 x 10^8 MWh of electricity from a facility comprising 12 modules of 60 MW(e), operating at 95% capacity over 60 years. The author highlighted that the main differences compared to large Light-Water Reactors (LWRs) lie in construction, operation, and decommissioning. Six impact categories were analyzed: water depletion, fossil depletion, metal depletion, climate change, human toxicity, and ionizing radiation. The results indicated that most impacts are associated with the fuel cycle processes. Furthermore, when compared to previous studies on conventional nuclear reactors and other energy sources like coal and natural gas, the environmental impacts of the studied SMR were lower [25].

4. CONCLUSIONS

The literature review, grounded in economic theory, has highlighted the importance of valuing the environment. It was observed that including environmental costs in decision-making is crucial for evaluating the advantages and disadvantages of specific energy sources, using a single measure of benefits and costs: money. The bibliographic research also identified key works addressing calculation methodologies for measuring environmental damage and externalities, reinforcing the relevance of the topic in the energy sector.

Assessing existing methodologies for calculating environmental costs reveals a well-established framework, particularly for routine operational assessments. However, the scarcity of specific studies for nuclear energy sources still complicates comparisons with other energy sources.

The literature review also showed that studies using Life Cycle Assessment (LCA) approach pay more attention to the impact of nuclear plant construction and decommissioning phases. Significant considerations include the substantial material requirements for large-scale construction projects and concerns regarding radioactive waste generation at the end of reactor operation. Another critical issue addressed in such studies is the high land occupation requirements, including exclusion areas and safety barriers for potential accidents. The difficulty in interpreting and comparing the environmental impacts of different categories quantitatively was also emphasized, highlighting the importance of normalization and weighting according to the amount of energy generated by each source.

Recognizing that ignoring certain phases may lead to underestimating environmental costs, there is an understanding that considering phases beyond reactor operation, such as construction and decommissioning—despite their complexity—would assist in obtaining more precise results.

Therefore, as a future perspective, a calculation program is being developed to estimate environmental costs, considering the unique characteristics of each project phase separately. This initiative aims to enhance the accuracy and comprehensiveness of environmental cost assessments in the nuclear sector.

Despite the clear environmental advantages of nuclear energy, especially when normalized per unit of electricity generated, public opinion remains a challenge. While there is no ideal energy generation system for all aspects, evaluating the benefits and challenges of each source is essential, and presenting them clearly becomes mandatory.

This observation emphasizes the ongoing importance of environmental impact assessments and comparisons between energy sources. Decision-making in energy policy requires reliable information and data, along with clear methodologies, aiming for a more sustainable and responsible approach to meet global energy needs.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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