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# Environmental Costs of Nuclear Reactors: a Literature Review

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## 1. Introduction

Providing reliable and affordable energy to a growing population while simultaneously reducing environmental impacts poses a significant challenge. To assess the feasibility of various available energy sources, it is necessary to consider price, availability, and their environmental impacts [1].

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

The future of nuclear energy encompasses decommissioning reactors reaching the end of their operational life, along with technological perspectives, including the consolidation of third and fourth-generation reactors, especially the construction of Small Modular Reactors (SMRs) [3]. Therefore, 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 commonly referred to in the literature as external costs, environmental costs, or externalities, so that their pricing allows the environment to cease being an unlimited and free resource. The inclusion of such costs assists in conservation tools and decision-making at a sustainable level [4].

Thus, for a comprehensive analysis of the viability of the nuclear source within the parameters of sustainability, it is necessary to consider the environmental costs involved in all phases of the life cycle of

nuclear power plants, including the phases of construction, operation, and decommissioning.
This ongoing research project aims to develop a program for calculating the environmental cost of Brazilian nuclear power plants and future SMRs. The purpose of this abstract is to present the literature review already conducted. It was possible to find environmental valuation studies for various sectors of the economy; however, the main references of projects and research related to the electric power sector will be presented.
The motivation for this work arose from the need for a comprehensive assessment of the environmental costs associated with nuclear power plants. A thorough 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 by the need for alternatives in the electrical sector of both the country and the world.

## 2. Methodology

This study was conducted as qualitative research through a literature review. It is a component of an ongoing project; therefore, the research is not exhaustive and is continually updated throughout the project's development.

## 3. Results and Discussion

Studies on the environmental impacts and external costs of energy generation have been conducted since the early 1990s. During that time, the 'External Costs of Energy' (ExternE) project emerged, initiated by the European Commission, to assess externalities associated with electricity generation. The development of the proposed methodology employed a bottom-up methodological approach, known in the literature as the Impact Pathway Approach (IPA). In this approach, environmental impacts in monetary terms are evaluated based on specific local and technology data, as well as the characteristics of pollutant receptors and their dose-response functions [5].

One of the reports in the series developed under the ExternE project outlines the application of the methodology for the eight stages of the nuclear fuel cycle in France. For the electricity generation phase, a 900 MW(e) Pressurized Water Reactor (PWR) was used as a reference. The monetary valuation of impacts on human health resulted in an estimated total cost of 0.47 mECU/kWh[1], without considering any discount rate. From this value, the operational cost represented 89%, construction 7%, and decommissioning 4% [7].

This project comprised a series of reports between 1991 and 2005, focusing on fossil, nuclear, and renewable sources. Using the developed methodologies, numerous studies were published in different countries and contexts, establishing it as the primary reference for valuation methodology in the energy sector. However, the literature review revealed that many works available in the literature use the methodology developed by the ExternE Project, with some simplifications, primarily focusing on the valuation of human health impacts due to particulate material emissions and impacts on climate change through the release of gases into the atmosphere. In this case, nuclear power plants typically show negligible environmental costs, as they do not produce significant greenhouse gases during the electricity generation process [8].

However, to achieve a more accurate estimate of external costs, some authors argue that health damages caused by the emission of radionuclides during electricity production should be taken into account. This was the case in a study conducted to compare major electricity generation technologies in Lithuania. The environmental costs of each kWh of electricity produced were calculated by multiplying the marginal value per unit of emission by the quantity of pollutants emitted at each production stage. The results indicated hydropower and wind sources with the lowest external costs. Nuclear power plants showed lower external costs than all fossil fuel-based technologies but higher than renewable energy-based technologies, except for technologies using biomass [9].

[1] The ECU (European Currency Unit) was the official monetary unit of the European Monetary System before the euro. Although it was an accounting unit, not a currency, it was used to determine exchange rates and reserves among member countries [6].

Despite the limited number of studies specifically developed for the nuclear sector, the International Atomic Energy Agency (IAEA) has developed the SIMPACTS tool (an acronym for Simplified Approach of Estimating Impacts of Electricity Generation), which allows the assessment of external costs during routine operations of nuclear power plants, through a simplified approach [10].

The SIMPACTS program's initial version was used to evaluate the environmental impacts of electricity generation in Indonesia. The comparison of two coal-fired, two natural gas, and one nuclear power plants resulted in lower costs for the nuclear source, followed by natural gas plants [11].

In Brazil, the environmental costs of electricity generation from the nuclear power plants Angra 1, 2, and 3 were calculated using the SIMPACTS program (2006 version). The results were compared with data from the Balakovo reactor, the Serra da Mesa hydroelectric plant, and a generic coal-fired power plant in France, all with the same generating capacity, as included in the program. According to the calculations, nuclear reactors exhibited a lower environmental cost compared to the other analyzed sources [12].

Furthermore, literature review has identified works with the objective of assessing and estimating the environmental impacts of energy sources. Although these works do not aim at valuing environmental costs, they analyze the environmental impacts of energy generation sources and serve as important references. Most of these studies employ a Life Cycle Assessment (LCA) approach, involving data collection across all phases of the life cycle of the object of study. In this case, the impact of the construction and decommissioning phases of nuclear power plants receives more attention. The need for a large quantity of materials for a large-scale project and concerns about the generation of radioactive waste at the end of reactor operation are emphasized [13]. Another issue addressed in this type of work is the high need for land occupation, with requirements such as exclusion zones and safety barriers for potential accidents [14]. Additionally, the difficulty in interpreting and comparing the environmental impacts of different categories quantitatively highlights the importance of normalization and weighting according to the amount of energy generated by each source [15].

## 4. Conclusions

A review of the literature on existing methodologies for calculating the environmental cost of nuclear reactors revealed a well-established framework, especially for assessing routine operations. Nevertheless, the scarcity of specific studies continues to impede comparisons with other energy sources. On the other hand, works using life cycle assessment approaches suggest that ignoring certain phases may result in underestimating environmental costs. Thus, it is understood that considering phases beyond reactor operation, such as construction and decommissioning, though highly complex, would assist in the process to obtain more accurate results.

As part of future work, an evaluation program is being developed to estimate environmental costs, considering the unique characteristics of each phase of the project separately. This initiative aims to enhance the accuracy and comprehensiveness of environmental cost assessments in the nuclear sector.

Despite the apparent environmental advantages of nuclear energy, particularly when normalized in relation to generated electricity, addressing 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 realization emphasizes the ongoing importance of environmental impact assessments and comparisons between sources. Decision-making in the realm of energy policies requires reliable information and data, with clear methodologies, aiming for a more sustainable and responsible approach to meet global energy needs.

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