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SYSTEMIC LIFE CYCLE ASSESSMENT OF NUCLEAR POWER PLANT BASED ON SMALL MODULAR REACTORS AND RENEWABLE ENERGY SYSTEMS UNDER CONTINUOUS AND SYNCHRONOUS ELECTRICITY SUPPLY REQUIREMENTS: IMPLICATIONS FOR NET-ZERO TRANSITION PATHWAYS

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1. Introduction

Decarbonizing electricity systems is one of the central requirements for achieving long-term climate mitigation targets and supporting the transition toward low-carbon energy systems [10,12,17]. In this context, nuclear and renewable energy technologies are frequently identified as key components of future electricity supply portfolios due to their low direct greenhouse gas (GHG) emissions [9,16]. Life Cycle Assessment (LCA) has become an essential methodology for evaluating the environmental performance of these technologies by accounting for impacts associated with resource extraction, fuel supply chains, infrastructure construction, operation, maintenance, and decommissioning [1,2,22,24].

Previous LCA studies have consistently demonstrated the low life-cycle carbon intensity of both nuclear and renewable electricity generation systems [6,16,23,25,26]. However, comparative assessments are often influenced by differences in the service effectively provided by each technology [16,22,24]. While nuclear power plants and reservoir-based hydropower systems can deliver continuous and synchronous dispatchable electricity, wind and photovoltaic systems are inherently variable and may require complementary dispatchable generation or energy storage to ensure reliable electricity supply and grid stability [4,10,11,16].

From a functional equivalence perspective, comparing technologies that provide different levels of availability and reliability may lead to distorted environmental conclusions [22,24]. In Brazil, the electricity required to compensate renewable intermittency is commonly supplied through reserve capacity mechanisms, predominantly based on natural gas-fired thermal power plants dispatched by the National Electric System Operator (ONS) [4,13]. Consequently, excluding complementary generation from environmental assessments may underestimate the impacts associated with the firm, continuous, and synchronous electricity delivery [16,22,24].

Small Modular Reactors (SMRs) have recently attracted significant interest due to their potential to provide reliable low-carbon electricity with high operational availability, modular deployment, and enhanced flexibility for integration into future decarbonized energy systems [9,14,23]. Nevertheless, comparative environmental assessments between SMRs and renewable technologies under equivalent electricity supply conditions remain limited in the literature [6,723,26].

Therefore, this study evaluates the life-cycle environmental performance of an integral Pressurized Water Reactor (iPWR)-based Small Modular Reactor system, represented by the NuScale VOYGR-12 configuration [14], and compares it with major renewable electricity generation technologies under a common functional framework. The analysis incorporates transmission losses and complementary thermal generation required to ensure firm, continuous, and synchronous electricity supply to a defined load center. The objective is to investigate how functional equivalence assumptions influence the comparative environmental performance of nuclear and renewable electricity systems.

2. Methodology

2.1 Functional Equivalence Framework

Comparative evaluation was based on a functional equivalence framework that considered continuous synchronous electricity delivery to a defined load center. Accordingly, the assessment incorporated electricity transmission losses and complementary dispatchable generation as needed to ensure an uninterrupted and synchronous electricity supply.

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The functional unit was defined as 1 MWh of electricity effectively delivered to a hypothetical consumer located in Araçariguama, São Paulo State, Brazil, over a 60-year operational period equivalent to the design lifetime of the reference nuclear power plant [14].

Unlike conventional comparative LCAs that rely exclusively on gross electricity generation, this approach sought to establish a common functional basis across technologies with distinct operational characteristics, availability factors, and supply reliability levels [22,24].

2.2 Life Cycle Assessment Modeling

Environmental performance was evaluated through an attributional cradle-to-grave Life Cycle Assessment (LCA) conducted in accordance with ISO 14040 and ISO 14044 standards [1,2,22,24]. Computational modeling was performed using SimaPro 10.3.0.3 [15] coupled with the Ecoinvent 3.10 database operating under the APOS-U (Allocation at the Point of Substitution – Unit Process) framework [3,18].

Environmental impacts were quantified using the ReCiPe 2016 Midpoint (H) method [8] and the IPCC AR6 Global Warming Potential (GWP100) methodology [5,12]. Although ten impact categories were evaluated, Climate Change, expressed as gCO_2eq/kWh, was adopted as the primary indicator for comparative assessment among electricity generation systems.

System boundaries included infrastructure construction, fuel supply chains, electricity generation, operation and maintenance activities, electricity transmission, and end-of-life management [1,2,22,24]

2.3 Electricity System Configuration

The reference nuclear system was represented by the NuScale VOYGR-12 design, consisting of twelve 60 MWe integral Pressurized Water Reactor (iPWR) modules, totaling 720 MWe of installed capacity [14]. Two regional scenarios were evaluated. The U.S. scenario considered the current fuel cycle involving internationalized uranium supply from major producing countries and fuel-cycle services, including conversion, enrichment, and fuel fabrication, performed at facilities operating in North America [19]. The Brazilian scenario was represented by a prospective configuration incorporating domestic uranium mining and processing, national enrichment capabilities associated with the future commercial operation of Brazil's uranium enrichment infrastructure, while maintaining uranium conversion activities in the United States, as uranium conversion accounts for only about 6% of the total nuclear fuel cost [19].

The main systemic difference between the two scenarios lies in the regional electricity mix and energy resources embedded in the industrial stages of the front-end fuel cycle. The Brazilian scenario uses the predominantly renewable Brazilian interconnected System (SIN) [4], whereas the U.S. scenario relies on the SERC/WECC electricity mix with significant fossil fuel participation [3,18,20].

Renewable electricity systems were modeled considering representative high-resource regions in Brazil. Reservoir-based hydropower was represented by the São Simão complex (MG), wind generation by installations located in Piauí (PI), and photovoltaic generation by utility-scale systems in Juazeiro (BA). In all cases, Araçariguama (SP) was considered the final load center.

Transmission and transformation losses were explicitly incorporated into system design. Losses of 11.5% were considered for hydropower systems and 14.3% for wind and photovoltaic systems. All renewable systems were sized to deliver the same net electricity output as the reference SMR configuration at the load center.

Because wind and photovoltaic technologies cannot independently guarantee a firm and continuous electricity supply, complementary natural gas-fired thermal generation was incorporated to ensure reliable electricity delivery [4,13]. Reservoir-based hydropower and SMR systems were assumed capable of providing a firm, continuous, and synchronous electricity supply without additional backup requirements [4,9,14].

3. Results and Discussion

3.1 Life-Cycle Performance of the SMR Reference System

The environmental performance of the reference SMR system was initially evaluated for the Brazilian and U.S. fuel-cycle configurations. Climate Change was adopted as the primary indicator for

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comparative analysis, while additional impact categories were used to verify the consistency of the modeled systems. The results obtained for the principal impact categories are summarized in Table I.

As shown in Table 1, the Brazilian SMR scenario achieved a climate change impact of approximately 6.64 g CO_2 eq/kWh, whereas the U.S. scenario reached 8.22 g CO_2 eq/kWh, representing a reduction of nearly 20% for the Brazilian configuration. This difference is mainly due to the lower carbon intensity of the Brazilian electricity matrix, which is used at several stages of the front-end fuel cycle.

Table I: LCA Modeling (SimaPro) for the U.S. and Brazilian Scenarios

IMPACT CATEGORIES SimaPro 10.03.Recipe 2016	UNITS	SMR-IPWR BR SCENARIO	SMR-IPWR US SCENARIO	Δ% (BR→US)
Global warming	kg CO_2 eq/MWh	6.636	8.221	19.28%
Ionizing radiation	kBq Co^{60} eq/MWh	1.718E+04	4.135E+05	95.85%
Terrestrial ecotoxicity	kg 1,4-DCB /MWh	871.321	544.280	-60.09%
Freshwater ecotoxicity	kg 1,4-DCB /MWh	2.683	1.824	-47.05%
Human carcinogenic toxicity	kg 1,4-DCB /MWh	10.466	8.249	-26.87%
Human non-carcinogenic toxicity	kg 1,4-DCB /MWh	270.053	170.016	-58.84%
Land use	m^2a crop eq /MWh	0.988	0.473	-108.75%
Mineral resource scarcity	kg Cu eq /MWh	1.523	1.496	-1.81%
Fossil resource scarcity	kg oil eq /MWh	2.461	2.154	-14.25%
Water consumption	m^3/MWh	1.805	1.851	2.45%

The obtained values are consistent with results reported in the scientific literature for advanced light-water reactor technologies, which typically range between approximately 5 and 12 g CO_2eq/kWh. Front-end fuel-cycle activities and infrastructure construction were identified as the dominant contributors to climate change impacts in both scenarios, while operational impacts remained comparatively low due to the absence of direct fossil-fuel combustion during electricity generation.

Additional differences were observed in the ionizing radiation impact category, mainly due to background processes in regional electricity mixes, particularly coal-related upstream activities in the U.S. scenario [3,18]. The comparison refers only to the modeled additional dose, excluding natural background radiation. The U.S. result corresponds to approximately 0.217% of the collective detriment associated with the annual additional dose limit recommended by the ICRP [27], whereas the Brazilian scenario, about 24 times lower, corresponds to 0.00898%. This result confirms that the radiological contribution of the evaluated nuclear cycle is negligible compared with naturally occurring radiation sources.

Otherwise, differences in land use and ecotoxicity were mainly associated with the hydropower-dominated Brazilian electricity mix represented in the Ecoinvent database [3,18]. Despite the noticeable relative variation between scenarios, the absolute impacts remained low.

3.2 Comparative Performance Under Functional Equivalence Conditions

After establishing the environmental performance of the reference SMR system and verifying its consistency with published literature, the analysis was expanded to compare nuclear and renewable electricity systems under equivalent electricity supply conditions [16,22,24].

When evaluated as stand-alone generation technologies, run-of-river hydropower, wind power, and photovoltaic systems exhibited relatively low life-cycle climate change impacts. However, these technologies do not inherently guarantee continuous electricity supply and therefore require complementary dispatchable generation to ensure synchronous and reliable electricity delivery to the load center [4,10,11,13].

After incorporating transmission losses and natural gas-fired backup generation, substantial differences emerged among the evaluated systems. The photovoltaic-thermal configuration reached 667 g CO_2 eq/kWh, while the wind-thermal system achieved 231 g CO_2 eq/kWh. The run-of-river hydropower-thermal system presented 102 g CO_2 eq/kWh. In contrast, the Brazilian SMR scenario remained at 6.64 g CO_2 eq/kWh.

These results indicate that environmental comparisons based solely on electricity generation may substantially underestimate the impacts associated with reliable electricity supply. Once equivalent

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delivery conditions are imposed, the contribution of complementary thermal generation becomes a dominant factor influencing overall environmental performance [16,22,24].

3.3 Implications of Functional Equivalence Assumptions

The results demonstrate that comparative environmental assessments of electricity generation technologies are highly sensitive to the definition of the service being evaluated [16,22,24]. While conventional LCAs frequently compare technologies on the basis of gross electricity generation, actual electricity systems must satisfy additional requirements related to reliability, continuity of supply, and transmission [4,10,11].

The adoption of a functional equivalence framework incorporating transmission losses and complementary dispatchable generation significantly altered the comparative performance of the evaluated technologies. These findings suggest that assessments based exclusively on generated electricity may not fully capture the environmental implications associated with delivering equivalent electricity services to final consumers [16,22,24]. Consequently, the results highlight the importance of explicitly defining functional equivalence conditions in comparative LCA studies of electricity systems, particularly when technologies with substantially different operational characteristics are evaluated.

4. Conclusions

This study evaluated the life-cycle environmental performance of a SMR-based nuclear power system and compared it with major renewable electricity generation technologies under equivalent electricity supply conditions.

The results demonstrated that the Brazilian SMR configuration achieved a climate change impact of approximately 6.64 g CO_2 eq/kWh, remaining within the range reported in the international literature for advanced nuclear technologies [6,23,25,26]. Differences observed between the Brazilian and U.S. scenarios were primarily associated with the carbon intensity of the electricity systems supporting the construction of the plant and front-end fuel-cycle activities.

More importantly, the adoption of a functional equivalence framework significantly influenced the comparative results obtained for the evaluated technologies. When transmission losses and complementary natural gas-fired generation required to ensure firm, continuous, and synchronous electricity delivery were incorporated into the assessment, substantial increases in climate change impacts were observed for intermittent renewable systems.

These findings indicate that comparative environmental assessments of electricity generation technologies are strongly affected by the definition of the service being evaluated [16,22,24]. Assessments based exclusively on gross electricity generation may not fully capture the environmental implications associated with delivering equivalent electricity services to final consumers. Therefore, the explicit consideration of functional equivalence conditions represents an important methodological requirement for future comparative LCA studies involving electricity generation systems with different operational characteristics and reliability requirements.

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This study includes 27 bibliographic references, which will be presented in the complete research paper.

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