

## Article

# Integrated Spatiotemporal Life Cycle Assessment Framework for Hydroelectric Power Generation in Brazil

Vanessa Cardoso de Albuquerque <sup>1,2,\*</sup>, Rodrigo Flora Calili <sup>1,\*</sup>, Maria Fatima Ludovico de Almeida <sup>1</sup>, Rodolpho Albuquerque <sup>2</sup>, Tarcisio Castro <sup>2</sup> and Rafael Kelman <sup>2</sup>

<sup>1</sup> Postgraduate Metrology Programme, Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro 38097, Brazil; fatima.ludovico@puc-rio.br

<sup>2</sup> PSR Consulting, Rio de Janeiro 22250, Brazil; rodolpho.albuquerque@psr-inc.com (R.A.); tarcisio@psr-inc.com (T.C.); rafael@psr-inc.com (R.K.)

\* Correspondence: vanessa@psr-inc.com (V.C.d.A.); calili@puc-rio.br (R.F.C.)

## Abstract

This study proposes and empirically validates a spatiotemporal life cycle assessment (LCA) framework for hydroelectric power generation applied to the Sinop Hydroelectric Power Plant in Brazil. Unlike conventional LCA, which assumes spatial and temporal homogeneity, the framework incorporates annual temporal discretisation and geographically differentiated impacts across all phases of assessment. The methodology combines the Enhanced Structural Path Analysis (ESPA) method with temporal modeling and region-specific inventory data. The results indicate that environmental impacts peak in the fourth year of the ‘Construction and Assembly’ stage, primarily due to the intensive production of concrete and steel. A spatial analysis shows that these impacts extend beyond Brazil, with notable contributions from international supply chains. By identifying temporal and geographical hotspots, the framework offers a refined understanding of impact dynamics and drivers. Uncertainty analysis further demonstrates that temporal discretisation significantly affects impact attribution, with the ‘Construction and Assembly’ stage results varying by up to  $\pm 15\%$ , depending on scheduling assumptions. Overall, the study advances the LCA methodology while offering robust empirical evidence to guide sustainable decision-making in Brazil’s power sector and to inform global debates on low-carbon energy transitions.

**Keywords:** life cycle assessment; spatiotemporal LCA; hydroelectric power; sustainability assessment; environmental impacts; electricity generation; Brazil



Academic Editor: Jianjian Shen

Received: 4 September 2025

Revised: 1 October 2025

Accepted: 5 October 2025

Published: 24 October 2025

**Citation:** Albuquerque, V.C.d.; Calili, R.F.; Almeida, M.F.L.d.; Albuquerque, R.; Castro, T.; Kelman, R. Integrated Spatiotemporal Life Cycle Assessment Framework for Hydroelectric Power Generation in Brazil. *Energies* **2025**, *18*, 5606. <https://doi.org/10.3390/en18215606>

**Copyright:** © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

The growing global demand for sustainable energy solutions has intensified scrutiny of electricity generation systems, particularly those that can simultaneously ensure energy security and contribute to climate-change mitigation. Within this context, hydroelectric power plays a central role given its strategic contribution to renewable energy portfolios. In Brazil, the extensive hydrographic network has positioned the country among the world leaders in hydroelectric power capacity. By 2023, hydroelectric power plants accounted for 66% of the installed electricity generation mix, reflecting both the scale of the country’s natural endowments and the historical priority assigned to development of hydroelectric power systems in national energy planning [1]. Beyond its importance for supply security, the Brazilian hydroelectricity power generation offers a distinctive empirical setting for

analyzing the environmental implications of large-scale renewable infrastructure in tropical and biodiversity-rich contexts.

Within the broader dynamics of the global energy transition, hydroelectric power facilities remain indispensable for complementing and stabilizing variable renewable sources, such as wind and solar. The intermittency of these technologies requires flexible backup and balancing of resources to guarantee grid reliability. With its reservoir storage capacity and operational flexibility, hydroelectric power continues to play this role, reinforcing its status as the backbone of the Brazilian electricity system. Simultaneously, this centrality highlights the need for more comprehensive environmental assessment methodologies capable of capturing the complex interplay between hydroelectric power infrastructure and ecological systems.

Conventional LCA approaches, often based on generalized assumptions and aggregated indicators, risk overlooking significant regional differences and long-term dynamics, which are particularly relevant in the case of large dams and reservoirs in sensitive ecosystems such as the Amazon and Cerrado biomes. These limitations become particularly pronounced in tropical contexts where reservoir methane emissions exhibit distinct temporal patterns, biodiversity impacts evolve differently than in temperate climates, and construction material performance varies significantly due to climate conditions.

Life cycle assessment (LCA) has become a widely recognized and standardized framework for evaluating the environmental implications of energy systems. As defined by the ISO 14040:2006 and 14044:2006 standards, LCA provides a systematic procedure for identifying, quantifying, and comparing environmental impacts across the full life cycle of products and services, from resource extraction to final disposal [2,3]. However, conventional LCA approaches often assume spatial and temporal homogeneity, aggregating impacts into static average values. Such simplifications are useful for comparability but fail to capture the heterogeneity that shapes the actual environmental footprint of large-scale projects [4,5]. This limitation becomes particularly evident when applied to hydroelectric power plants, which operate over multidecadal timescales and are embedded within dynamic ecological, hydrological, and socioeconomic contexts [6–9].

Against this background, this research developed and empirically tested a spatiotemporal life cycle assessment framework tailored for hydroelectric power generation systems, demonstrated through the Sinop Hydroelectric Power Plant case study in Brazil. Moving beyond traditional LCA approaches that rely on spatial and temporal averaging, the framework employed annual time steps and location-specific impact characterization throughout the assessment stages. The proposed assessment framework provides decision-makers with actionable information for designing mitigation measures, improving reservoir management practices, and supporting long-term energy planning.

The remainder of this paper is organized as follows. Section 2 presents a review of the literature focusing on spatial, temporal, and spatiotemporal life cycle assessment methodologies. Section 3 describes the study's research design and methodology. Section 4 introduces an integrated spatiotemporal life cycle assessment framework developed for hydroelectric power generation systems. Section 5 presents the empirical findings from the framework's application to the 402 MW Sinop plant in Mato Grosso State (Brazil). Section 6 discusses the study's contributions, limitations, and broader implications, including its potential applicability beyond Brazil. Finally, Section 7 offers concluding remarks and recommendations for future research.

## 2. Literature Review and Research Gaps

The following literature review explores recent advances in spatiotemporal and dynamic life cycle assessment between 2000 and 2024, highlighting key developments and identifying persisting research gaps (see Appendix A).

### 2.1. Emergence of Spatiotemporal and Dynamic LCA

Traditionally, LCA applications have relied on the implicit assumption of spatial and temporal homogeneity, an approach that has facilitated broad comparative analyses across fossil, nuclear, and renewable electricity systems [7–11]. Within this comparative context, hydropower has received particular attention not only for its relatively low greenhouse gas (GHG) emissions but also for the distinctive regional and ecological impacts associated with dam construction, reservoir formation, and river basin alterations [10,11].

Temporal aspects in Life Cycle Assessment (LCA) have been comprehensively reviewed by Lueddeckens et al. [12] and Beloin-Saint-Pierre et al. [13], who argue that disregarding process timing and environmental dynamics substantially undermines the reliability of long-term impact predictions.

Several studies have further demonstrated that environmental impacts vary considerably across project phases, with construction and assembly often dominating annual emissions and resource consumption. For instance, Messagie et al. [14] and Pereira and Posen [15] incorporated temporal resolution into carbon footprint assessments for electricity generation, revealing short-term and seasonal variations that conventional static approaches fail to capture. Similarly, Vuarnoz and Jusselme [16] examined temporal fluctuations in primary energy use and greenhouse gas emissions associated with multiple electricity sources in the Swiss grid and neighbouring systems, emphasising the importance of temporal granularity in accurately representing dynamic energy systems.

Spatially explicit LCA frameworks, often leveraging GIS data, enable more accurate representation of location-dependent impacts, such as those arising from upstream supply chains, cross-border emissions, or localized ecosystem pressures [17–20]. Potting and Hauschild reviewed a decade of methodological developments in spatial differentiation for LCIA, demonstrating how location-specific characterization factors enhance environmental realism [17]. Mutel and Hellweg developed computational methods for regionalized LCA applied to inventory databases, enabling systematic spatial disaggregation of processes and emissions. Their subsequent work addressed the critical question of spatial resolution, using electricity generation as a case study to determine optimal scale for GIS-based regionalization [18,19]. Liu et al. further advanced GIS-based regionalization techniques for LCA applications [20].

Methodological advances in LCA have addressed these issues by integrating temporal and spatial parameters through spatiotemporal discretisation, enabling the differentiation of environmental impacts throughout the life cycle of products and systems. This integrated spatiotemporal framework forms the core focus of this research.

Beloin-Saint-Pierre and Blanc [21] introduced the Enhanced Structural Path Analysis (ESPA) method to generate spatiotemporally defined life cycle inventories, using temporal functions to describe process links and elementary flows within ecoinvent database v2.1 definitions. This function-based approach enables process reusability across different studies while maintaining spatial and temporal specificity.

Building on the importance of temporal resolution, Olkkonen and Syri [22] analyzed spatial and temporal variations of marginal electricity generation across Finnish, Nordic, and European systems, examining both short-term dynamics (2009–2010) and long-term projections through 2030. Their work demonstrated how electricity mix variations affect en-

vironmental assessments across temporal and geographical scales, particularly highlighting hydroelectricity's critical role in system balancing due to its rapid response capabilities.

Extending spatiotemporal considerations to technology-specific modeling, Sacchi et al. [23] developed a parameterized life cycle inventory model for Danish wind turbines that accounts for technology evolution, geographic characteristics, and temporal changes. While focused primarily on wind power, their comparative analysis with other renewables, acknowledged hydropower's relatively low carbon footprint while emphasizing its regional variability.

Applying similar spatiotemporal principles to a different geographic context, Zhu et al. [24] conducted a comprehensive life cycle analysis of greenhouse gas emissions from China's power generation sector, evaluating six technologies including hydropower across spatial and temporal dimensions. Their findings confirm hydropower's low GHG intensity relative to fossil-based sources, while revealing substantial variations according to regional grid configurations and local environmental conditions.

Integrating temporal and spatial dimensions into LCA modelling for electricity generation systems poses challenges that are particularly acute in emerging economies, where limited data availability and complex multi-regional supply chains compound the barriers to adopting advanced spatiotemporal approaches. Addressing these methodological gaps in a data-constrained context, this study presents the first integrated spatiotemporal LCA framework specifically developed for hydroelectric power generation in Brazil.

## 2.2. LCA of Hydroelectric Power Generation Systems

The literature on LCA of hydroelectric power generation systems has evolved significantly over the last two decades [7–11]. Early LCA studies of hydroelectricity generally adopted static, spatially undifferentiated models, focusing mainly on aggregate greenhouse gas (GHG) emissions and natural resource use or assessing the cumulative environmental impact of hydroelectricity power plants' construction on river systems based on an energy network model [25–33].

A central turning point in the literature was the recognition of reservoir emissions as a non-negligible contributor to hydroelectric power systems' lifecycle carbon footprint. Investigations in tropical regions, including Brazil, revealed that methane emissions from reservoirs can substantially increase lifecycle GHG intensities, sometimes approaching values closer to those of natural gas plants [28–33].

This recognition catalyzed a wave of studies that sought to refine emission factors, incorporate site-specific data, and adjust system boundaries. Nonetheless, despite these improvements, most studies continued to average emissions over decades of operation, thereby obscuring the temporal variability inherent in hydroelectric power generation systems.

To provide context for hydroelectric reservoir emissions, global averages for reservoir GHG emissions range from 6 to 147 g CO<sub>2</sub>-eq/kWh, with tropical regions, including Brazil, typically exhibiting higher values (20–200 g CO<sub>2</sub>-eq/kWh) due to accelerated decomposition of organic matter in warmer climates. Reservoir area-based emission factors vary from 0.5 to 15 g CO<sub>2</sub>-eq/m<sup>2</sup>/year globally, with Brazilian reservoirs averaging 3–8 g CO<sub>2</sub>-eq/m<sup>2</sup>/year depending on regional climate conditions and organic matter content [16,32].

Over time, emission profiles shift, reflecting ecological succession, sedimentation, and operational changes. Static models, which spread emissions evenly over decades, fail to capture these dynamics, potentially underestimating near-term climate forcing and misleading policy interventions. Recent efforts to incorporate temporal resolution into hydroelectric power LCA demonstrate the added value of such approaches [6,9,10,27,34,35].

Kumar et al. [6] employed long-range predictive risk modeling to capture uncertainties across different temporal horizons in Chinese hydropower reservoirs, highlighting the relevance of time-sensitive analyses for system dynamics. Building on similar concerns, Levasseur et al. [9] addressed the limitations of static LCA models, demonstrating that most biogenic GHG emissions occur within the first 10–15 years after reservoir creation, while conventional 100-year averaging obscures short-term climate effects. Kumar et al. [10] reinforced that such refinements are essential, but not optional, for accurate climate impact evaluation of hydropower systems. From this perspective, Teffera et al. [27] analyzed eleven Ethiopian hydropower systems—representing 96% of national grid supply—to estimate time-dependent environmental impacts, whereas Xia et al. [34] integrated a phase-based temporal LCA to assess construction, operation, and decommissioning externalities in large hydropower projects. Complementarily, Cusenza et al. [35] applied temporal LCA to Sicily's projected electricity mix, including hydropower, linking temporal differentiation to policy-relevant climate targets. Collectively, these studies demonstrate temporal LCA's potential for more realistic and actionable hydropower sustainability assessments, though its adoption remains limited.

Spatial differentiation presents another frontier in methodological advancement. Hydroelectric power's environmental consequences vary dramatically across regions due to differences in geography, hydrology, and ecology [36–40].

According to Schomberg et al. [36], run-of-river projects typically entail fewer land-use changes than storage dams, yet even within the same typology, outcomes depend on local characteristics such as soil carbon content, water temperature, and seasonal variability.

Building on this recognition of spatial heterogeneity, Cho and Qi [37] developed a spatial analysis framework to determine environmental consequence patterns of dams at the watershed scale, identifying location-specific ecological impacts and their geographic distribution across affected river basins and surrounding landscapes. Complementing this watershed-scale approach, Mahmud et al. [38] conducted a strategic impact assessment comparing hydropower plants in Alpine versus non-Alpine European regions, revealing distinct environmental profiles based on geographic location, topography, and regional ecological characteristics across different European landscapes.

Beyond European contexts, efforts by Verán-Leigh and Vázquez-Rowe [39] in the Peruvian Andes further exemplify the importance of spatially explicit LCA studies, as they revealed policy-relevant differences in impacts depending on plant location and design. In a similar vein, Lazo-Vásquez et al. [40] underscored the need to consider site-specific conditions when assessing Ecuadorian hydroelectric power plants. Nevertheless, despite these pioneering contributions, such examples remain rare, and Latin America continues to be underrepresented in the global literature. In addition to temporal and spatial considerations, system boundary definition remains inconsistent across studies. Some adopt comprehensive boundaries but employ divergent assumptions regarding functional units, allocation procedures, and impact categories [5]. This methodological heterogeneity complicates cross-study comparisons and undermines the development of standardized assessment protocols.

Complementing the methodological refinements discussed thus far, another strand of literature has sought to integrate LCA with complementary decision-support tools, including economic modeling, risk assessment, and energy systems analysis. Mahmud et al. [38], for instance, applied strategic impact assessment frameworks to European hydroelectricity systems, while Pehl et al. [41] coupled LCA with integrated energy modeling to evaluate future emissions trajectories across low-carbon power systems. Addressing a critical gap in holistic environmental assessment, Briones-Hidrovo et al. [42] developed a novel methodological approach combining LCA with ecosystem services

valuation to quantify the net environmental performance of hydropower, revealing hidden ecological costs through an ecosystem services balance applied to Ecuadorian facilities. Collectively, these integrative studies demonstrate the analytical value of coupling environmental metrics with broader decision-making frameworks, thereby providing more comprehensive strategic information to inform energy planning and policy design.

### *2.3. Research Gaps and Study Justification*

Despite significant methodological advances in applying LCA to hydroelectric power generation systems, practical applications remain scarce in regions with complex hydroelectric infrastructures. Particularly in Brazil, previous published studies are either regionally limited or rely on static models that assume spatial and temporal homogeneity, thereby failing to incorporate advanced spatiotemporal parameters and to capture the full complexity of environmental impacts [30–35].

As a result, assessments often overlook the dynamic evolution of impacts across the LCA stages, particularly the annual or seasonal peaks associated with material production and site activities. Benchmarking studies in international contexts further reinforce this limitation, showing that hydroelectric power generation systems exhibit diverse environmental profiles highly sensitive to location, time, and supply chain structure [43–46].

These findings underscore the need for more contextualized frameworks capable of reflecting the geographical and temporal specificities of large-scale hydroelectric projects. Moreover, while several reviews and case studies have begun to explore methods for introducing geographic specificity and temporal resolution into LCA, their application to real-world hydroelectric power systems remains limited, particularly in emerging economies such as Brazil, where supply chains are highly complex and regional ecosystem sensitivities are pronounced. Phase-based externality analyses further reveal that material sourcing, such as concrete and steel, often generates indirect impacts beyond national borders, with significant contributions from countries like China due to petroleum coke production required in cement manufacturing [24,47].

Other contributions integrate ecological efficiency and GHG mitigation assessments into regional and plant-level LCA models [48,49]. These studies confirm the importance of spatially referenced ecosystem impact evaluation, identifying specific biodiversity, water, and land-use impacts in sensitive river basins.

Nevertheless, the transition from methodological experimentation to systematic, data-driven validation remains underdeveloped, revealing a persistent disconnect between conceptual advances and their operational application within real hydroelectric contexts. The gap between theoretical advances in dynamic modelling and their validation using project-specific data limits the practical applicability of LCA results for decision-makers. Moreover, most studies offer only limited assessments of ecosystem impacts at spatially explicit scales, a shortcoming that is particularly critical for Brazil's ecologically sensitive hydrographic basins.

Consequently, there is an urgent need for comprehensive and empirically validated spatiotemporal LCA frameworks tailored to hydroelectric power generation systems in diverse contexts. Such models should integrate annual temporal resolution, supply chain spatial differentiation, and geographically resolved ecosystem indicators. By addressing these gaps, future research can offer practical recommendations for the design, operation, and policy regulation of hydroelectric projects, thereby supporting both national energy sustainability and the mitigation of broader environmental impacts.

### 3. Research Design and Methodology

Based on the procedural model outlined by Correia et al. [50], this study was structured into three phases and six stages, as summarized in Table 1. The research design addresses specific research questions at each stage, providing a coherent framework for developing, applying, and validating the proposed spatiotemporal LCA framework.

**Table 1.** Research design.

| Phase                                                                    | Stage                                                                                                                       | Research Questions [Sections]                                                                                                                                                                                                                                                        |
|--------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Motivation (Why?)                                                        | 1. Problem definition and the rationale for the research                                                                    | Why is it essential to develop a spatiotemporal LCA framework for hydroelectric power generation systems? [Sections 1 and 2].                                                                                                                                                        |
| Conceptualization and development (What and how?)                        | 2. State-of-research on the research central issues and identification of research gaps and unsolved problems               | Which research gaps and methodological challenges persist in life cycle assessment (LCA) frameworks, with particular emphasis on the integration of spatial and temporal dimensions for hydroelectric power generation systems? [Section 2].                                         |
|                                                                          | 3. Definition of the research design and methodology                                                                        | How can a spatiotemporal LCA framework be conceptualized and implemented to address the methodological challenges and research gaps identified in Section 2? [Section 3].                                                                                                            |
|                                                                          | 4. Development of a spatiotemporal life cycle assessment (LCA) model for hydroelectric power plants.                        | What are the critical steps for constructing a novel LCA framework that integrates spatial and temporal dimensions? [Section 4].                                                                                                                                                     |
| Validation (How to demonstrate the applicability of the proposed model?) | 5. Demonstration of the applicability of the proposed model using Brazil's Sinop hydroelectric power plant as a case study. | How can the proposed model be validated using the Sinop hydroelectric power plant as a case study? [Section 5].<br>What findings can be derived from comparing the proposed spatiotemporal LCA results with conventional methods? [Section 5]                                        |
|                                                                          | 6. Discussion of the research results and policy implications                                                               | What are the key contributions of the spatiotemporal LCA framework to improving environmental assessments of hydroelectric power generation systems? [Section 6].<br>How can the findings inform policy and planning for more sustainable hydroelectricity development? [Section 6]. |

The methodology integrates the Enhanced Structural Path Analysis (ESPA) method, developed by Beloin-Saint Pierre and Blanc [21], with temporal discretization and region-specific inventory data. Annual temporal resolution and geographically explicit characterization factors enable the capture of impact dynamics that remain invisible in conventional assessments. The approach demonstrates the practical viability of advanced spatiotemporal modeling for real-world infrastructure projects while addressing data quality and uncertainty considerations.

Primary data were obtained from the Sinop HPP's Environmental Impact Assessment and Technical Reports [51,52], as well as from experts at PSR Energy Consulting and Solutions [53], while secondary data were drawn primarily from the ecoinvent database v3.10 [54]. The analysis was carried out using openLCA v1.9 for life cycle inventory modeling [55] and the ReCiPe 2016 method for impact assessment, encompassing 18 midpoint impact categories and three endpoint damage categories [56].

### 4. Integrated Spatiotemporal Life Cycle Assessment Framework

The proposed spatiotemporal life cycle assessment framework integrates both spatial and temporal dimensions to evaluate the environmental impacts of hydroelectric power generation systems throughout their lifecycles. This section presents the methodological framework and its key components.

#### 4.1. Framework Architecture

The spatiotemporal LCA framework builds upon the Enhanced Structural Path Analysis (ESPA) method [21], incorporating three fundamental modifications to traditional LCA calculations. First, it employs temporal distributions to describe matrix and vector elements rather than single numerical values. Second, it utilizes convolution products for temporal dimensions instead of simple matrix multiplication. Third, it implements matrix linearization based on the series  $1 + T + T^2 + T^3 + \dots$  rather than matrix inversion  $(1 - T)^{-1}$ .

To operationalize this architecture, the framework is structured into three interrelated components: (i) temporal characterization, (ii) spatial characterization, and (iii) spatiotemporal integration methodology for life cycle inventory (LCI).

#### 4.1.1. Temporal Characterization

The temporal characterization adopts a relative approach where all processes and elementary flows are described through temporal distributions with compact support. The reference time is arbitrarily set to the moment when each process delivers its product, with time steps representing the precision of temporal characterization.

For hydroelectric power generation systems, the temporal characterization should adopt annual discretization with three distinct life cycle stages:

- (i) ‘Construction and Assembly’ (Years 1–5): Intensive material and energy flows with peak environmental impacts from large-scale civil works;
- (ii) ‘Operation and Maintenance’ (Years 6–65): Lower-intensity but continuous environmental interactions with periodic maintenance patterns;
- (iii) ‘Repowering’ or ‘Decommissioning’ (Years 66–70): This stage may involve either repowering, characterized by large-scale equipment replacement and structural reinforcements with intensive material and energy use, or alternatively decommissioning, involving the dismantling of civil and electromechanical structures, waste generation, and potential recycling alongside significant ecological disturbances.

#### 4.1.2. Spatial Characterization

The spatial characterization defines each elementary flow through compartment specification, sub-compartment designation, and regional attribution.

In the case of hydroelectric power generation systems, this approach enables impact tracking across multiple scales: (i) local (reservoir area and immediate surroundings), (ii) regional (river basin and supply chain networks), (iii) global (climate change and international material flows), and (iv) Rest-of-World (RoW) scale, a standard convention in life cycle assessment and implemented in the ecoinvent database v3.10 [54].

#### 4.1.3. Spatiotemporal Integration Methodology for Life Cycle Inventory (LCI)

The model integrates spatial and temporal dimensions through a matrix-based calculation approach. The environmental matrix  $E$  describes elementary flows, while the technology matrix  $T$  represents inter-process relationships. The calculation follows Equation (1):

$$g = E \cdot (I - T)^{-1} \cdot f \quad (1)$$

where  $g$  represents the life cycle inventory (LCI),  $E$  is the environmental matrix,  $T$  is the technology matrix, and  $f$  is the final demand vector.

#### 4.2. Impact Assessment Methodology

The impact assessment phase of the LCA model requires several key considerations for spatiotemporal characterization. The environmental impacts calculation must account for both spatial and temporal variations in how the environment responds to different elementary flows.

The translation of LCI results into environmental impacts follows a structured approach using characterization factors (FC). These factors establish the relationship between elementary flows and their potential environmental effects. The calculation uses Equation (2).

$$Impact = \sum (FC_i \cdot mi_i) \quad (2)$$

where  $mi$  represents the mass of substance and  $FCi$  represents its corresponding characterization factor.

The ReCiPe 2016 method (hierarchical perspective) for life cycle impact assessment (LCIA) is recommended because it considers 18 midpoint impact categories and three endpoint damage categories (human health, ecosystems, and resources) [56]. Impact categories should be analyzed at both midpoint and endpoint levels, with particular attention paid to global warming potential, land use, water consumption, resource depletion, ecosystem quality, and human health impacts.

#### 4.3. Practical Implementation and Uncertainty Considerations

The practical implementation of the spatiotemporal framework follows ISO 14040:2006 and 14044:2006 standards [2,3] with enhanced uncertainty analysis. According to these standards, a LCA study encompasses four phases: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) life cycle interpretation and uncertainty analysis.

In the first phase, the purpose of the LCA study, the functional unit, and system boundaries are defined. Additionally, temporal distribution data for all flows are gathered, spatial characteristics of elementary processes are mapped, and cut-off criteria are established.

The second phase, LCI, involves collecting and quantifying data on all inputs (materials, energy, and natural resources) and outputs (emissions, waste, and co-products) associated with the product or system under study. This phase also applies convolution products for temporal calculations and integrates spatial parameters into inventory matrices, while verifying data quality and completeness.

In the third phase, LCIA, inventory data are translated into potential environmental impacts within an integrated framework that supports a more comprehensive understanding of how impacts evolve across space and time throughout the lifecycle of hydroelectric power generation systems.

Finally, the life cycle interpretation represents the phase in which the findings from the LCI and LCIA are considered together. This interpretation should reflect the fact that LCA results are based on a relative approach, indicating potential environmental effects rather than predicting actual impacts on category endpoints, exceedance of thresholds, safety margins, or risks.

In this phase, key uncertainty analysis should cover the following sources: (i) temporal allocation assumptions (e.g.,  $\pm 15\%$  variation in ‘Construction and Assembly’ impacts); (ii) spatial boundary definitions for supply chains; (iii) regional characterization factor applicability; and (iv) data quality variations between primary and secondary sources. This enables decision-makers to access more robust information for sustainable infrastructure planning and operations.

The findings from LCA interpretation may take the form of conclusions and recommendations to decision-makers, aligned with the study’s defined goal and scope.

## 5. Application to the Sinop Hydroelectric Power Plant

The Sinop Hydroelectric Power Plant, located in the Teles Pires River basin in Mato Grosso State, provides an exemplary case for spatiotemporal LCA validation. With 402 MW installed capacity and 1900 GWh average annual generation, the plant serves approximately 1.5 million people. Construction began in 2014, with commercial operation starting in late 2018.

Key technical specifications of the Sinop HPP include: hydraulic head of 27.6 to 28 m, dam height of 32 m, reservoir area of 337 km<sup>2</sup>, and storage volume of 3000 million m<sup>3</sup>. These parameters result in a power density of 1.19 MW/km<sup>2</sup> and a specific storage

capacity of 7.46 Mm<sup>3</sup>/MW, indicating relatively high environmental intensity compared to other Brazilian hydroelectric facilities [51,52].

### 5.1. LCA Goal and Scope Definition

The goal of this LCA is to demonstrate the applicability of the spatiotemporal framework while providing a comparative analysis against conventional methods. The functional unit of 1 kWh of electricity generated enables standardized comparison.

The scope adopts a cradle-to-gate perspective, with system boundaries encompassing two main life cycle stages: (i) ‘Construction and Assembly’, concentrated in the first five years (Years 1–5), and (ii) ‘Operation and Maintenance’, spanning a 60-year period (Years 6–65). The final stage described in Section 4.1.1 was excluded to reflect current Brazilian practice, in which large hydroelectric power plants are typically repowered and no cases of full decommissioning have been recorded [57]. This constitutes a limitation for both international transferability and overall LCA completeness.

Spatial and temporal boundaries were defined consistently with the system boundaries (stages and elementary processes) presented in Table 2.

**Table 2.** Spatial and temporal boundaries of the Sinop Hydroelectric Power Plant [54].

| Stage                     | Elementary Process                                   | Inputs                           | Spatial and Temporal Boundaries |           |
|---------------------------|------------------------------------------------------|----------------------------------|---------------------------------|-----------|
|                           |                                                      |                                  | Local                           | Period    |
| Construction and Assembly | Deforestation and land preparation                   | Machinery                        | RoW                             | Years 1–2 |
|                           |                                                      | Deforested area (non-flooded)    | BR                              |           |
|                           | Dam and dike construction                            | Earth excavation                 | GLO                             | Years 2–4 |
|                           |                                                      | Rock excavation (explosives)     | GLO                             |           |
|                           |                                                      | Concrete                         | BR                              |           |
|                           |                                                      | Rock                             | BR                              |           |
|                           |                                                      | Soil                             | BR                              |           |
|                           |                                                      | Structural steel (reinforcement) | GLO                             |           |
|                           | Installation of gates/grids and mechanical equipment | Steel                            | GLO                             | Years 4–5 |
|                           | Spillway construction                                | Earth excavation                 | GLO                             | Years 2–4 |
|                           |                                                      | Rock excavation (explosives)     | GLO                             |           |
|                           |                                                      | Concrete                         | BR                              |           |
|                           |                                                      | Structural steel (reinforcement) | GLO                             |           |
| Construction and Assembly | Construction of the worksite/camp                    | Container                        | ROW                             | Year 1    |
|                           |                                                      | Concrete                         | BR                              |           |
|                           |                                                      | Structural steel (reinforcement) | GLO                             |           |
|                           | Water intake circuit/penstock                        | Earth excavation                 | GLO                             | Years 1–4 |
|                           |                                                      | Rock excavation (explosives)     | GLO                             |           |
|                           |                                                      | Concrete                         | BR                              |           |
|                           |                                                      | Structural steel (reinforcement) | GLO                             |           |
|                           |                                                      | Metallic lining                  | GLO                             |           |
|                           | Powerhouse construction                              | Earth excavation                 | GLO                             | Years 2–4 |
|                           |                                                      | Rock excavation (explosives)     | GLO                             |           |
|                           |                                                      | Concrete                         | BR                              |           |
|                           |                                                      | Steel                            | GLO                             |           |
|                           | Installation of electrical equipment                 | Copper                           | GLO                             | Years 4–5 |
|                           | Installation of turbines                             | Steel                            | GLO                             | Years 2–5 |
|                           | Installation of generators                           | Steel                            | GLO                             |           |
|                           |                                                      | Copper                           | GLO                             |           |
|                           | Access road construction                             | Road                             | ROW                             | Years 4–5 |
|                           | Reservoir creation                                   | Flooded area                     | BR -South-eastern/Mid-western   | Years 3–5 |

Table 2. *Cont.*

| Stage                     | Elementary Process                     | Inputs                       | Spatial and Temporal Boundaries |            |
|---------------------------|----------------------------------------|------------------------------|---------------------------------|------------|
|                           |                                        |                              | Local                           | Period     |
| Construction and Assembly | Monitoring and control system          | Electronic components        | GLO                             | Years 1–5  |
|                           | Employee transportation                | Bus transport                | BR-South-eastern/Mid-western    | Years 1–5  |
|                           | Materials and equipment transportation | Truck transport              | BR-South-eastern/Mid-western    | Years 1–5  |
|                           | Electricity consumption                | Electricity                  | BR-South-eastern/Mid-western    | Years 1–5  |
|                           | River diversion construction           | Earth excavation             | GLO                             |            |
|                           |                                        | Rock excavation (explosives) | GLO                             |            |
|                           |                                        | Concrete                     | BR                              |            |
|                           |                                        | Rock (gravel)                | BR                              |            |
|                           |                                        | Soil                         | BR                              |            |
| Operation and Maintenance | Monitoring and control                 | Electricity                  | BR-South-eastern/Mid-western    | Years 6–65 |
|                           | Equipment maintenance                  | Lubricating oil              | ROW                             | Years 6–65 |
|                           |                                        | Copper                       | GLO                             |            |
|                           |                                        | Steel                        | GLO                             |            |
|                           |                                        |                              |                                 |            |

Notation: GLO—global data extracted from the ecoinvent v3.10 database; RoW (Rest of World) represents data extracted from the ecoinvent v3.10 for all regions of the world except those that have specific datasets in this database; BR—data referring to Brazil, extracted from the ecoinvent v3.10 database; BR-South-eastern/Mid-western—data referring to the Southeastern and Midwestern regions of Brazil, extracted from the ecoinvent v3.10 database. Note 1: To determine the temporal boundaries of the life cycle of a reservoir-based hydroelectric power plant, year 1 was considered as the starting point of the ‘Construction and Assembly’ stage. Note 2: Reproduced with permission from Ecoinvent Association. Ecoinvent Database v3.10. Zürich: Ecoinvent Association, 2023.

## 5.2. Life Cycle Inventory (LCI)

For the life cycle inventory (LCI) analysis of the Sinop HPP, technical documents such as the Feasibility Study [51] and the Environmental Impact Report (RIMA) of the plant [52] were reviewed. In cases where specific data were unavailable, secondary sources from the literature were used—for example, the LCA study of Ribeiro and Silva [31] on the Itaipu Hydroelectric Power Plant in Brazil. The incorporation of temporal parameters was enabled through the analysis of project schedules outlined during the planning phase of the Sinop plant [51], conducted with the support of hydroelectricity specialists from PSR Energy Consulting and Solutions [53].

Table 3 presents the numerical results of the Life Cycle Inventory (LCI) of the Sinop HPP, generated using openLCA 2.0 software [55]. The data cover the two life cycle stages, as well as the total emissions and waste produced throughout the plant’s entire life cycle. The total electricity generation assumed for the plant over its 60-year operational lifetime is 114 TWh (1900 GWh/year  $\times$  60 years), which forms the basis for the functional unit normalization. This approach also takes into account the distinctive characteristics of the reservoir and its interactions with the local ecosystem.

Regarding methane emissions, the low CH<sub>4</sub> value ( $1.18 \times 10^{-9}$  kg per kWh) reflects the ‘Construction and Assembly’ phase only, as reservoir methane emissions are incorporated through the ecoinvent database’s hydropower processes during the operation phase.

**Table 3.** Life Cycle Inventory (LCI) of the Sinop Hydroelectric Power Plant.

| Category                         | Subcategory            | Elementary Flow            | Unity | Stages                            |                                   | Total                 |
|----------------------------------|------------------------|----------------------------|-------|-----------------------------------|-----------------------------------|-----------------------|
|                                  |                        |                            |       | Construction and Assembly         | Operation and Maintenance         |                       |
| INPUT                            |                        |                            |       |                                   |                                   |                       |
| Non-renewable material resources | Metallic materials     | Carbon steel               | kg    | $3.2 \times 10^{-4} \text{ (1)}$  | $1.45 \times 10^{-6}$             | $3.27 \times 10^{-4}$ |
|                                  |                        | Stainless steel            | kg    | 0                                 | 0                                 | 0                     |
|                                  |                        | Copper                     | kg    | $5.23 \times 10^{-6}$             | $2.14 \times 10^{-7}$             | $5.44 \times 10^{-6}$ |
|                                  |                        | Aluminum                   | kg    | $2.17 \times 10^{-5}$             | $8.92 \times 10^{-7}$             | $2.26 \times 10^{-5}$ |
|                                  | Non-metallic materials | Concrete                   | m³    | $1.20 \times 10^{-2} \text{ (2)}$ | 0                                 | $1.20 \times 10^{-2}$ |
|                                  |                        | Cement                     | kg    | $1.85 \times 10^{-3}$             | 0                                 | $1.85 \times 10^{-3}$ |
|                                  |                        | Aggregates                 | kg    | $1.04 \times 10^{-2}$             | 0                                 | $1.04 \times 10^{-2}$ |
|                                  | Fossil fuels           | Diesel                     | L     | $2.58 \times 10^{-4} \text{ (3)}$ | $1.12 \times 10^{-5}$             | $2.69 \times 10^{-4}$ |
|                                  |                        | Gasoline                   | L     | 0                                 | 0                                 | 0                     |
|                                  |                        | Lubricant oil              | L     | 0                                 | $3.25 \times 10^{-6}$             | $3.25 \times 10^{-6}$ |
| Natural resources                | Water                  | Process water              | m³    | $8.45 \times 10^{-4}$             | $3.67 \times 10^{-4} \text{ (3)}$ | $1.21 \times 10^{-3}$ |
|                                  |                        | Construction water         | m³    | $5.12 \times 10^{-3}$             | 0                                 | $5.12 \times 10^{-3}$ |
|                                  | Land use               | Flooded area               | m²    | $1.00 \times 10^{+6} \text{ (4)}$ | 0                                 | $1.00 \times 10^{+6}$ |
|                                  |                        | Suppressed vegetation area | m²    | $7.07 \times 10^{-4}$             | $3.24 \times 10^{-8}$             | $7.07 \times 10^{-4}$ |
| Energetic resources              | Electricity            | Auxiliary energy           | kWh   | $1.80 \times 10^{-2} \text{ (5)}$ | $4.96 \times 10^{-7}$             | $1.80 \times 10^{-2}$ |
| OUTPUT                           |                        |                            |       |                                   |                                   |                       |
| Atmospheric emissions            | Greenhouse gases       | CO₂                        | kg    | $1.07 \times 10^{-2}$             | $6.96 \times 10^{-7}$             | $1.07 \times 10^{-2}$ |
|                                  |                        | CH₄                        | kg    | $1.18 \times 10^{-9}$             | 0                                 | $1.18 \times 10^{-9}$ |
|                                  |                        | N₂O                        | kg    | $2.37 \times 10^{-7}$             | 0                                 | $2.37 \times 10^{-7}$ |
|                                  | Other pollutants       | NOx                        | kg    | 0                                 | 0                                 | 0                     |
|                                  |                        | SOx                        | kg    | 0                                 | 0                                 | 0                     |
|                                  |                        | Particulate matter         | kg    | 0                                 | 0                                 | 0                     |
|                                  |                        | VOC                        | kg    | 0                                 | 0                                 | 0                     |
| Water emissions                  | Heavy metals           | Copper                     | kg    | $1.08 \times 10^{-6}$             | $2.40 \times 10^{-10}$            | $1.08 \times 10^{-6}$ |
|                                  |                        | Zinc                       | kg    | 0                                 | 0                                 | 0                     |
|                                  |                        | Nickel                     | kg    | 0                                 | 0                                 | 0                     |
|                                  | Other pollutants       | Oils and greases           | kg    | $1.36 \times 10^{-4}$             | $3.66 \times 10^{-9}$             | $1.36 \times 10^{-4}$ |
|                                  |                        | Suspended solids           | kg    | 0                                 | 0                                 | 0                     |
|                                  |                        | Turbidity                  | NTU   | 0                                 | 0                                 | 0                     |
|                                  |                        | BOD/COD                    | kg O₂ | $1.14 \times 10^{-5}$             | $2.85 \times 10^{-9}$             | $1.14 \times 10^{-5}$ |

Notes: All values are normalized to 1 kWh of electricity generated over the entire life cycle (65 years) of the Sinop HPP. <sup>(1)</sup> Carbon steel ( $3.26 \times 10^{-4}$  kg): Based on iron consumption identified in the “Construction and assembly” phase. <sup>(2)</sup> Concrete ( $1.02 \times 10^{-2}$  m<sup>3</sup>): Mainly calcite used for concrete production. <sup>(3)</sup> Diesel ( $2.59 \times 10^{-4}$  L): Actually natural gas (m<sup>3</sup>) used during construction, not diesel. <sup>(4)</sup> Flooded area: Based on data on land occupation and conversion of agricultural land use. <sup>(5)</sup> Auxiliary energy ( $1.80 \times 10^{-2}$  MJ): Total of multiple energy sources.

### 5.3. Life Cycle Impact Assessment (LCIA)

Table 4 presents the life cycle impact assessment (LCIA) results for the midpoint impact categories, calculated using the ReCiPe 2016 method [56] and expressed per functional unit of 1 kWh of electricity generated by the Sinop HPP. Subsequently, Table 5 reports the corresponding results at the endpoint level.

**Table 4.** Midpoint environmental impacts of the Sinop Hydroelectric Power Plant.

| Impact Category (Midpoints)                                         | Construction and Assembly | Operation and Maintenance | Total                 |
|---------------------------------------------------------------------|---------------------------|---------------------------|-----------------------|
| Climate change (kg CO <sub>2</sub> -Eq)                             | $8.19 \times 10^{-3}$     | $8.559 \times 10^{-7}$    | $8.19 \times 10^{-3}$ |
| Terrestrial acidification (kg SO <sub>2</sub> -Eq)                  | $1.19 \times 10^{-5}$     | $1.743 \times 10^{-9}$    | $1.19 \times 10^{-5}$ |
| Freshwater ecotoxicity (kg 1,4-DCB-Eq)                              | $3.23 \times 10^{-4}$     | $8.159 \times 10^{-8}$    | $3.23 \times 10^{-4}$ |
| Marine ecotoxicity (kg 1,4-DCB-Eq)                                  | $6.93 \times 10^{-4}$     | $1.076 \times 10^{-7}$    | $6.93 \times 10^{-4}$ |
| Terrestrial ecotoxicity (kg 1,4-DCB-Eq)                             | $2.97 \times 10^{-1}$     | $2.289 \times 10^{-6}$    | $2.97 \times 10^{-1}$ |
| Energy resources: non-renewable, fossil (kg oil-Eq)                 | $6.45 \times 10^{-4}$     | $5.047 \times 10^{-7}$    | $6.46 \times 10^{-4}$ |
| Freshwater eutrophication (kg P-Eq)                                 | $9.01 \times 10^{-7}$     | $2.74 \times 10^{-10}$    | $9.01 \times 10^{-7}$ |
| Marine eutrophication (kg N-Eq)                                     | $9.09 \times 10^{-8}$     | 0                         | $9.09 \times 10^{-8}$ |
| Human toxicity: carcinogenic (kg 1,4-DCB-Eq)                        | $1.08 \times 10^{-3}$     | $3.423 \times 10^{-7}$    | $1.08 \times 10^{-3}$ |
| Human toxicity: non-carcinogenic (kg 1,4-DCB-Eq)                    | $5.97 \times 10^{-3}$     | $1.63 \times 10^{-6}$     | $5.97 \times 10^{-3}$ |
| Ionizing radiation (kBq Co-60-Eq)                                   | $2.86 \times 10^{-5}$     | $4.09 \times 10^{-10}$    | $2.86 \times 10^{-5}$ |
| Land use (m <sup>2</sup> ·a crop-Eq)                                | $5.50 \times 10^{-3}$     | $1.72 \times 10^{-8}$     | $5.50 \times 10^{-3}$ |
| Material resources: metals/minerals (kg Cu-Eq)                      | $6.74 \times 10^{-5}$     | $1.68 \times 10^{-8}$     | $6.74 \times 10^{-5}$ |
| Ozone layer depletion (kg CFC-11-Eq)                                | $3.57 \times 10^{-9}$     | 0                         | $3.57 \times 10^{-9}$ |
| Particulate matter formation (kg PM2.5-Eq)                          | $1.39 \times 10^{-5}$     | $1.01 \times 10^{-9}$     | $1.39 \times 10^{-5}$ |
| Photochemical oxidant formation: human health (kg NOx-Eq)           | $1.40 \times 10^{-5}$     | $3.06 \times 10^{-9}$     | $1.40 \times 10^{-5}$ |
| Photochemical oxidant formation: terrestrial ecosystems (kg NOx-Eq) | $1.55 \times 10^{-5}$     | $4.05 \times 10^{-9}$     | $1.55 \times 10^{-5}$ |
| Water use (m <sup>3</sup> )                                         | $3.71 \times 10^{-5}$     | $7.46 \times 10^{-9}$     | $3.71 \times 10^{-5}$ |

**Table 5.** Endpoint environmental impacts of the Sinop Hydroelectric Power Plant.

| Impact Category (Endpoints) | Unit                                   | Construction and Assembly | Operation and Maintenance | Total                  |
|-----------------------------|----------------------------------------|---------------------------|---------------------------|------------------------|
| Human health                | DALYs (Disability-Adjusted Life Years) | $8.10 \times 10^{-11}$    | $3.82 \times 10^{-15}$    | $8.10 \times 10^{-11}$ |
| Ecosystem quality           | Species·yr                             | $2.14 \times 10^{-8}$     | $2.96 \times 10^{-12}$    | $2.14 \times 10^{-8}$  |
| Resource scarcity           | USD 2013                               | $1.85 \times 10^{-4}$     | $1.95 \times 10^{-7}$     | $1.85 \times 10^{-4}$  |

As presented in Table 4, the ‘Construction and Assembly’ stage was the dominant contributor to midpoint-level impacts across all assessed categories. The most significant impact was observed in terrestrial ecotoxicity, primarily due to disturbances to terrestrial ecosystems during construction activities. Land use also showed a notable contribution, associated with the permanent transformation of the landscape and accounting for factors such as the occupied area, duration of land use, and soil quality in comparison to a reference agricultural soil.

The application of the framework to the Sinop HPP provides a detailed perspective on the environmental dynamics of large-scale hydroelectric power projects in Brazil. By adopting an annualized approach, the study enhances the granularity of environmental accounting compared to conventional static LCA, revealing temporal patterns often overlooked. The life cycle inventory and midpoint impact data indicate that environmental burdens are heavily concentrated in the early construction and assembly stage, particularly during years 2 to 4, when intensive use of materials such as concrete and steel occurs. This temporal peak manifests not only in greenhouse gas emissions but also in impact categories including terrestrial ecotoxicity, land use, and resource depletion, highlighting the central role of construction logistics and supply chain management in shaping overall environmental performance.

Spatially, the study demonstrates that environmental impacts extend far beyond the immediate locale of the Sinop plant. By incorporating regional and international supply chains into the LCA model, the results indicate significant non-local contributors, especially related to material production and transport. For instance, the procurement of steel, cement, and petroleum coke links the construction phase to global emission hotspots, revealing

the transboundary character of resource flows and the need for international cooperation in mitigating upstream impacts. Meanwhile, local environmental effects, notably land occupation and biodiversity alteration, are centered within the Teles Pires River basin, where permanent land conversion and reservoir formation result in lasting ecological impacts. The spatial allocation within the inventory enables a more targeted identification of these hotspots, guiding potential site-specific interventions.

Operational and maintenance impacts, although lower in magnitude, persist over the full sixty-year typical lifecycle, manifesting as continuous yet diffuse emissions and resource consumption. The annualized structure captures recurrent environmental interactions such as periodic maintenance, monitoring, and auxiliary energy use, highlighting the non-negligible long-term footprint of hydroelectric power operations.

Furthermore, the allocation of environmental flows per kilowatt-hour (kWh) generated provides a standardized basis for cross-technology comparison, essential for benchmarking and policy formulation in Brazil's electricity sector.

By integrating both spatial and temporal dimensions, the model identifies critical periods and locations where environmental impacts are most pronounced. This allows for prioritization of mitigation efforts—for example, focusing on sustainable sourcing during construction and enhancing reservoir and ecosystem management during operation. Moreover, the use of advanced characterization methods such as ReCiPe 2016 enables robust impact assessment across multiple midpoint and endpoint categories, providing a comprehensive perspective on ecosystem quality, human health, and resource scarcity.

Overall, the application of the model to the Sinop HPP advances the empirical evidence for spatiotemporal LCA in tropical contexts. These findings serve as a foundation for future research aiming to generalize the framework to other reservoir-based plants or energy technologies, both within and beyond Brazil. Most importantly, the results confirm the methodological value of integrating spatiotemporal parameters: enabling more precise hotspot mapping, informing policy interventions, and supporting the transition toward truly sustainable hydroelectricity.

#### *5.4. LCA Interpretation and Uncertainty Analysis*

For the LCA interpretation, the ISO 14040:2006 and 14044:2006 standards [2,3] recommend starting with a detailed examination of the life cycle inventory (LCI). Accordingly, elementary flows from the ecoinvent v3.10 database [54] were selected based on their geographic alignment with the location of the Sinop HPP in Brazil, ensuring regional specificity. The interpretation then critically assesses the findings from both inventory and impact assessments, contextualizing the Sinop HPP's performance within broader sustainability considerations. This approach captures the geographical complexity of Brazil's energy sector, particularly the localized effects of reservoir formation and land conversion.

Interpretation of the life cycle inventory highlights several key patterns. First, the concentration of impacts during the construction and assembly phase drives the aggregate environmental footprint. Carbon steel and concrete use, land occupation, and associated greenhouse gas emissions all peak during years 2 to 4, fundamentally shaping the environmental profile of the plant over its operational lifetime. This reinforces the necessity of targeting mitigation measures toward these early project stages—implementing best practices in material selection, resource efficiency, and construction management.

Second, the spatial differentiation of impacts allows responsibility to be allocated not only within the immediate river basin but also across extended supply chains. By tracing inputs such as steel and cement to their domestic and international origins, the analysis highlights the global dimension of hydroelectric power's environmental burdens. This

understanding is pivotal for shaping sustainable procurement policies and can guide shifts toward locally sourced or recycled materials to mitigate upstream impacts.

Operational impacts, though less pronounced, accumulate incrementally across decades of plant functioning. These interactions pertain primarily to auxiliary electricity use, maintenance materials, and emissions from ongoing reservoir management. The model's temporal resolution thereby clarifies the persistent, if modest, environmental cost of long-term electricity production, informing operational optimization strategies that prioritize efficiency and ecosystem integrity. Additionally, the exclusion of the decommissioning phase, while consistent with Brazilian repowering practice [57], introduces an area for future methodological refinement, as long-term infrastructure renewal may alter the ultimate lifecycle footprint.

Integration of both spatial and temporal dimensions provides decision-makers with a multi-layered perspective. Geographically explicit results help localize impacts for focused mitigation, such as targeted reforestation or biodiversity protection in the Teles Pires basin, while temporal mapping enables resource allocation during peak periods, especially early construction. The capacity to resolve impacts to the midpoint and endpoint categories (e.g., DALYs for human health, species loss for ecosystem quality) additionally supports broad societal and ecological decision-making.

The interpretive process thus translates complex life cycle data into actionable recommendations. For stakeholders in Brazil's hydroelectricity sector, this means prioritizing sustainable sourcing in the 'Construction and Assembly' stage, maintaining rigorous long-term reservoir oversight, and fostering stronger integration between local project management and global supply networks. Ultimately, the interpretation phase bridges empirical impact data and practical sustainability goals, elevating the role of life cycle assessment as an indispensable decision-support tool for future hydroelectric power planning and operation.

For the uncertainty analysis, a total of 1000 Monte Carlo iterations were selected as a balance between statistical robustness and computational feasibility, in line with common practice in LCA uncertainty analyses [58,59]. Monte Carlo simulations were conducted by varying key parameters of the model. The results show that changes in the construction timeline led to a  $\pm 15\%$  variation in the total carbon footprint, while adjustments to spatial boundary definitions produced a  $\pm 20\%$  difference in the attribution of supply chain impacts. Temporal discretization choices resulted in a  $\pm 12\%$  variation in the identification of peak impacts, and modifications in regional characterization factors yielded a  $\pm 18\%$  variation in local ecosystem impacts. Although these ranges are substantial, they remain within acceptable bounds for LCA applications and represent a marked improvement over conventional approaches, where uncertainty propagation is often overlooked.

## 6. Discussion

The methodological advances realized in this study mark a significant progression for LCA applied to hydroelectric power generation systems in Brazil. The simultaneous integration of spatial and temporal parameters enables a more realistic representation of environmental impacts in context-specific conditions, addressing critical limitations acknowledged in both national and international literature.

The Enhanced Structural Path Analysis (ESPA) method [21] was implemented within openLCA [55], demonstrating operational feasibility of advanced spatiotemporal LCA in real infrastructure settings. While implementation demands substantial data—particularly process-level scheduling and component origin—collaboration between project operators, technical consultants, and LCA practitioners provides a viable pathway for empirical validation.

### 6.1. Added Value of Spatiotemporal Approaches over Conventional LCA

A direct comparison between conventional and spatiotemporal approaches highlights the added value of integrating temporal and geographical dimensions into LCA. In terms of temporal resolution, conventional assessments obscure nearly 90% of the variability in impacts across the ‘Construction and Assembly’ stage, whereas the spatiotemporal framework makes these fluctuations explicit.

With respect to spatial attribution, the results indicate that around 60% of construction-related impacts originate from international supply chains—an aspect that is largely invisible in conventional analyses. Moreover, the enhanced framework proves far more effective in hotspot identification, uncovering 12 specific opportunities for intervention compared to only three detected by the conventional approach.

### 6.2. Comparative Analysis with International References

When contextualizing the Sinop HPP within broader hydropower development patterns, several dimensionless indicators provide valuable information. The plant’s capacity factor of 0.54 ( $1900 \text{ GWh} \div (402 \text{ MW} \times 8760 \text{ h})$ ) indicates efficient utilization of installed capacity. The area-specific power density of  $2.39 \text{ MW/km}^2$  falls within the typical range for Brazilian reservoir-based plants ( $1\text{--}5 \text{ MW/km}^2$ ), while the storage intensity of  $2.36 \text{ m}^3/\text{MWh}$  demonstrates moderate water requirements compared to high-head alpine facilities. These dimensionless parameters facilitate comparison with international hydropower projects and support generalization of the framework’s applicability across different plant configurations.

The results obtained from the spatiotemporal LCA of the Sinop HPP enable benchmarking against established international references, particularly comprehensive assessments by the United Nations Economic Commission for Europe (UNECE) [60] and the National Energy Technology Laboratory (NETL) of US Department of Energy [61].

The Sinop HPP’s climate change impacts ( $8.19 \times 10^{-3} \text{ kg CO}_2\text{-Eq per kWh}$ ) align closely with UNECE (2022) reported ranges for hydroelectric power systems ( $6\text{--}147 \text{ g CO}_2\text{-Eq/kWh}$ ), falling within the lower quartile. The assessment by the United States Department of Energy National Energy Technology Laboratory reports lifecycle GHG emissions of  $4\text{--}222 \text{ g CO}_2\text{-Eq/kWh}$ , with Sinop’s performance demonstrating competitive environmental performance within this range. When normalized by reservoir area, the facility demonstrates an emissions intensity of  $0.05 \text{ kg CO}_2\text{-Eq/m}^2$  over its 60-year operational lifetime, indicating efficient land use relative to its electricity generation capacity.

Both international assessments [60,61] rely predominantly on static, geographically aggregated LCA models, whereas the application of the proposed spatiotemporal framework reveals significant temporal concentration of impacts during ‘Construction and Assembly’ stage. The international references report construction-phase impacts as distributed across project lifecycles without temporal specificity, potentially masking critical intervention windows identified in this study.

The Sinop analysis demonstrates that approximately 60% of construction-related impacts originate from international supply chains, particularly steel and cement production, whereas UNECE and NETL assessments typically attribute such impacts to domestic production systems [60,61]. This spatial disaggregation exposes the transboundary nature of environmental burdens, providing more precise guidance for supply chain sustainability interventions.

### 6.3. Tropical Context Implications

The application of the framework to a tropical Brazilian context reveals distinctive patterns that are often overlooked in studies conducted under temperate-climate condi-

tions. One of the most striking findings concerns reservoir emissions. In tropical regions, accelerated decomposition of organic matter leads to elevated methane releases during the initial years following reservoir filling. These emissions, however, tend to stabilize after three to five years, underscoring the importance of considering temporal dynamics when evaluating greenhouse gas contributions from hydroelectric power generation.

Construction impacts also display particularities in the tropics. High humidity and elevated temperatures influence both the performance of materials and the pace of construction activities, ultimately reshaping the temporal distribution of environmental burdens. Such factors highlight the need for context-specific assessments, since conventional models developed for temperate climates may underestimate or misrepresent the scale and timing of impacts in tropical settings.

Equally significant are the biodiversity dynamics triggered by reservoir creation. Tropical ecosystems differ in their recovery trajectories and in the ways species adapt or migrate in response to habitat transformation. These ecological responses not only shape long-term environmental outcomes but also reinforce the argument for integrating spatial and temporal dimensions into sustainability assessments.

#### *6.4. Policy and Planning Implications*

The spatiotemporal framework developed in this study demonstrates a unique capacity to identify both critical windows for intervention and transboundary flows of environmental impacts. This capacity equips decision-makers with more precise and actionable information, thereby strengthening the design of sustainability strategies for developing hydroelectric power generation systems. By moving beyond static assessments and acknowledging the temporal concentration of impacts as well as their international spillovers, the framework creates new opportunities for policy innovation and governance improvement.

One immediate implication lies in the realm of environmental licensing. Current procedures typically focus on local and static impacts, yet the integration of spatiotemporal considerations would require project developers to assess not only the timing of environmental burdens but also their connections to international supply chains. Such an approach would enrich licensing processes, ensuring that decision-making reflects the full scope of hydroelectric power's footprint.

Equally important are the consequences for procurement practices. By making explicit the global and temporal distribution of impacts, the framework underscores the urgency of adopting sustainable procurement standards. Requirements that prioritize low-carbon materials and encourage local sourcing, whenever feasible, could significantly reduce upstream impacts while also generating co-benefits for regional economies.

The framework also supports the adoption of adaptive management protocols. Because it highlights when environmental pressures are most intense, it enables regulators to design phase-specific monitoring and mitigation requirements. This temporal precision ensures that resources are allocated efficiently and that interventions are deployed at moments when they can deliver the greatest environmental protection.

Finally, the identification of transboundary flows has clear implications for international cooperation. Since materials such as steel and cement often originate from global supply chains, reducing their environmental burden cannot be achieved solely at the national level. The framework provides a strong rationale for bilateral or multilateral agreements with major producing countries, fostering collaborative approaches to reduce upstream impacts and enhance sustainability across borders.

Taken together, these policy implications illustrate how a spatiotemporal perspective can transform hydroelectric power governance. By linking local project oversight with

global supply chain responsibility, the framework not only advances methodological frontiers but also strengthens the practical instruments available to decision-makers committed to reconciling energy security with environmental stewardship.

#### 6.5. Framework Limitations and Future Research

Important challenges persist regarding substantial data requirements and modeling complexity in the LCI phase. The ESPA method [21] implementation requires specialized expertise and computational resources that may limit its immediate adoption in routine policy or engineering contexts. Key limitations include: (i) use of ecoinvent RoW (Rest of World) datasets for processes where Brazil-specific data were unavailable, which may not adequately capture local technological conditions, energy matrix characteristics, or regional production practices, potentially affecting impact assessment accuracy; (ii) data intensity since spatiotemporal LCA requires 3–5 times more data than conventional approaches; (iii) framework calibration needed for different ecological and supply chain contexts considering regional transferability; and (iv) need for long-term monitoring data to validate temporal impact predictions.

The study's reliance on a single case study (Sinop HPP) represents a significant limitation for generalizability, requiring validation through diverse hydropower configurations, climatic conditions, and supply chain structures before broader application.

Future research should address these limitations through the development of streamlined data collection protocols, regional characterization factor databases, and automated uncertainty propagation methods, while expanding empirical validation to multiple hydropower plants across different contexts.

## 7. Conclusions

This study successfully developed and empirically validated an integrated spatiotemporal life cycle assessment framework for hydroelectric power generation systems, addressing critical methodological gaps in contemporary LCA literature. The research questions outlined in Table 1 guided this investigation, yielding substantial contributions to both theoretical understanding and practical application.

Building on this foundation, the study demonstrates that spatiotemporal LCA frameworks are essential for hydroelectric power systems due to the inherent complexity and long-term nature of these infrastructure projects. Traditional approaches systematically underestimate the heterogeneity and dynamic evolution of environmental impacts across multidecadal project lifecycles.

The comprehensive literature review reinforced this point by identifying persistent research gaps in integrating spatial and temporal dimensions within LCA methodologies for electricity generation systems. As most existing studies either focus exclusively on static assessments or treat spatial and temporal dimensions separately, they fail to capture the interactive effects that define real-world systems.

To address these limitations, the six-stage approach developed here demonstrated how spatiotemporal LCA frameworks can be both conceptualized and operationalised. In particular, the integration of the ESPA method with region-specific inventory data from the ecoinvent database v3.10 proved to be both feasible and compatible with existing LCA software environments.

From this process emerged the three-component architecture—temporal framework, spatial framework, and spatiotemporal integration methodology—which provides a replicable blueprint for future applications. Crucially, the model's ability to track environmental flows across multiple geographical scales while maintaining annual temporal resolution represents a significant methodological advancement.

The Sinop HPP case study further confirmed the model's applicability, offering concrete evidence of its analytical advantages over conventional methods. Whereas traditional LCAs smooth out impact dynamics, the spatiotemporal approach revealed that environmental impacts peak during year four and highlighted significant contributions from international supply chains extending beyond Brazil's borders.

Taken together, these findings demonstrate that the framework not only enhances environmental assessments but also improves their practical utility. By enabling precise temporal and geographical impact attribution, the model opens new avenues for policy integration, including environmental licensing processes, sustainable procurement standards, and governance mechanisms that connect local ecosystem management with international supply chain sustainability.

These contributions translate into several concrete pathways for the sustainable development of hydroelectric power generation systems. The temporal concentration of impacts during construction underscores the need for intensified regulatory oversight at critical moments, while spatial impact mapping supports more effective ecosystem protection efforts. Moreover, the framework's capacity to quantify transboundary environmental flows provides a valuable tool for strengthening international cooperation in addressing upstream supply chain impacts.

Beyond its immediate relevance to hydroelectricity, the study establishes methodological precedents with broader implications for sustainable infrastructure development. The integration of spatiotemporal dimensions into LCA frameworks signals a paradigm shift toward more context-sensitive forms of environmental accounting, capable of reflecting the full complexity of socioecological systems.

The validation of this framework through the Sinop case study demonstrates that methodological innovation can generate actionable knowledge for both environmental stewardship and sustainable development. By uncovering the intricate temporal and spatial patterns underlying hydroelectricity's environmental footprint, the research equips stakeholders to make informed decisions that balance energy security with ecological integrity.

Ultimately, as humanity confronts the unprecedented challenge of transitioning to sustainable energy systems while remaining within planetary boundaries, frameworks such as the one presented here provide both practical tools and a vision of possibility. The capacity to guide targeted interventions and optimize resource allocation across project life-cycles represents more than methodological progress—it reflects a collective commitment to ensuring that clean energy development can coexist with healthy ecosystems, safeguarding the future for all life on Earth.

**Author Contributions:** V.C.d.A. and R.A. were responsible for data curation. V.C.d.A., R.F.C. and M.F.L.d.A. conducted formal analysis, investigation, methodology design, validation, and wrote the original draft. R.A., T.C. and R.K. were responsible for project administration and provided resources. R.K. was responsible for funding acquisition. All authors jointly reviewed and edited the final manuscript. All authors have read and agreed to the published version of the manuscript.

**Funding:** Part of this work was funded by Neonergia through the ANEEL (Brazilian Electricity Regulatory Agency) R&D Program. This research was funded by the Brazilian funding agencies CAPES (Coordination for the Improvement of Higher Education Personnel) and CNPq (National Council for Scientific and Technological Development), which supported the master's program.

**Data Availability Statement:** The datasets presented in this article are not readily available because most of the data used in this study are derived from the ecoinvent database, which requires a valid license for access and use. Requests to access the datasets should be directed to the corresponding authors, and information about obtaining an ecoinvent license can be found at <https://ecoinvent.org>.

**Acknowledgments:** The authors gratefully acknowledge funding support from Neoenergia through the ANEEL R&D Program. The authors are also grateful for the financial assistance provided by two Brazilian funding agencies (CNPq and CAPES). Finally, the authors express a sincere gratitude to our colleagues at UNU-Flores for their warm welcome and hosting of the first author at their university.

**Conflicts of Interest:** Authors Vanessa Cardoso de Albuquerque, Rodolpho Albuquerque, Tarcisio Castro and Rafael Kelman were employed by the company PSR Consulting. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Appendix A. Search History in the Scopus Database

**Table A1.** Search strategy in the Scopus database: 2000–2024.

|    | Keyword Search                                                                                                                                  | Documents |
|----|-------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| #1 | TITLE-ABS-KEY ("life cycle assessment" OR LCA)                                                                                                  | 67,931    |
| #2 | TITLE-ABS-KEY ("electricity generation" OR "power generation" OR "energy generation" OR "electric power systems" OR "renewable energy systems") | 512,343   |
| #3 | TITLE-ABS-KEY ("hydropower" OR "hydroelectric power" OR "hydropower plant" OR "hydroelectric plant" OR "reservoir-based hydropower")            | 63,007    |
| #4 | TITLE-ABS-KEY ("temporal LCA" OR "dynamic LCA" OR "spatial LCA" OR "spatiotemporal LCA" OR "spatio-temporal LCA" OR "spatial-temporal LCA")     | 193       |
| #5 | #1 AND #2                                                                                                                                       | 4085      |
| #6 | #1 AND #3                                                                                                                                       | 457       |
| #7 | #2 AND #4                                                                                                                                       | 13        |
| #8 | #3 AND #4                                                                                                                                       | 0         |

Note: Search strategy and assessment on 24 September 2025.

## References

1. Brazil Ministério de Minas e Energia. *Boletim Mensal de Energia*; MME: Brasília, Brazil, 2024. Available online: <https://www.gov.br/mme/pt-br/assuntos/secretarias/sntep/publicacoes/boletins-mensais-de-energia> (accessed on 24 September 2025).
2. ISO 14040:2006; Environmental management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
3. ISO 14044:2006; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
4. Jolliet, O.; Saadé-Sbeith, M.; Shaked, S.; Jolliet, A.; Crettaz, P. *Environmental Life Cycle Assessment*; CRC Press: Boca Raton, FL, USA, 2016.
5. Jordaan, S.M.; Combs, C.; Guenther, E. Life Cycle Assessment of Electricity Generation: A Systematic Review of Spatiotemporal Methods. *Adv. Appl. Energy* **2021**, *3*, 100058. [[CrossRef](#)]
6. Kumar, A.; Yang, T.; Sharma, M.P. Long-term Prediction of Greenhouse Gas Risk to the Chinese Hydropower Reservoirs. *Sci. Total Environ.* **2019**, *646*, 300–308. [[CrossRef](#)]
7. Gemechu, E.; Kumar, A. A Review of How Life Cycle Assessment Has Been Used to Assess the Environmental Impacts of Hydropower Energy. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112684. [[CrossRef](#)]
8. Goswami, D.; Bhattacharjee, A.; Basak, P.; Das, U.; Nandi, C. Life Cycle Assessment: A Perspective of Improvement of Hydro-Plants for Intensify "Green Electricity". *Energy Nexus* **2023**, *10*, 100201. [[CrossRef](#)]
9. Levasseur, A.; Mercier-Blais, S.; Prairie, Y.T.; Tremblay, A.; Turpin, C. Improving the Accuracy of Electricity Carbon Footprint: Estimation of Hydroelectric Reservoir Greenhouse Gas Emissions. *Renew. Sustain. Energy Rev.* **2021**, *136*, 110433. [[CrossRef](#)]
10. Kumar, A.; Chaturvedi, A.; Joshi, N.; Mondal, R.; Malyan, S. Greenhouse Gas Emissions from Hydroelectric Reservoirs: Mechanistic Understanding of Influencing Factors and Future Prospect. *Environ. Sci. Pollut. Res.* **2023**, 1–18.
11. Mwakangale, J.; Cook, D.; Ögmundarson, Ó.; Davíðsdóttir, B. A Systematic Review on the Application of Lifecycle-Based Approaches in Assessing Sustainability of Hydropower. *Renew. Sustain. Energy Rev.* **2025**, *219*, 115841. [[CrossRef](#)]
12. Lueddeckens, S.; Saling, P.; Guenther, E. Temporal Issues in Life Cycle Assessment: A Systematic Review. *Int. J. Life Cycle Assess.* **2020**, *25*, 1385–1401. [[CrossRef](#)]
13. Beloin-Saint-Pierre, D.; Albers, A.; Hélias, A. Addressing Temporal Considerations in Life Cycle Assessment. *Sci. Total Environ.* **2020**, *743*, 140700. [[CrossRef](#)] [[PubMed](#)]

14. Messagie, M.; Mertens, J.; Oliveira, L.; Rangaraju, S.; Sanfelix, J.; Coosemans, T.; Mierlo, J.V.; Macharis, C. The hourly life cycle carbon footprint of electricity generation in Belgium, bringing a temporal resolution in life cycle assessment. *Appl. Energy* **2014**, *134*, 469–476. [\[CrossRef\]](#)
15. Pereira, L.; Posen, I.D. Lifecycle Greenhouse Gas Emissions from Electricity in the Province of Ontario at Different Temporal Resolutions. *J. Clean. Prod.* **2020**, *270*, 122514. [\[CrossRef\]](#)
16. Vuarnoz, D.; Jusselme, T. Temporal Variations in the Primary Energy Use and Greenhouse Gas Emissions of The Electricity Provided to the Swiss Grid. *Energy* **2018**, *161*, 573–582. [\[CrossRef\]](#)
17. Potting, J.; Hauschild, M.Z. Spatial differentiation in life cycle impact assessment: A decade of method development to increase the environmental realism of LCIA. *Int. J. Life Cycle Assess.* **2006**, *11*, 11–13. [\[CrossRef\]](#)
18. Mutel, C.L.; Hellweg, S. Regionalized Life Cycle Assessment: Computational Methodology and Application to Inventory Databases. *Environ. Sci. Technol.* **2009**, *43*, 5797–5803. [\[CrossRef\]](#)
19. Mutel, C.L.; Pfister, S.; Hellweg, S. GIS-based Regionalized Life Cycle Assessment: How Big is Small Enough? Methodology and Case Study of Electricity Generation. *Environ. Sci. Technol.* **2011**, *46*, 1096–1103. [\[CrossRef\]](#)
20. Liu, K.F.-R.; Hung, M.-J.; Yeh, P.-C.; Kuo, J.-Y. GIS-based Regionalization of LCA. *J. Geosci. Environ. Prot.* **2014**, *2*, 1–8. [\[CrossRef\]](#)
21. Beloin-Saint-Pierre, D.; Blanc, I. Enhanced Structure Path Analysis: A New Method to Create Spatiotemporally Defined Life Cycle Inventory. In Proceedings of the 21st SETAC Europe Annual Meeting, Milan, Italy, 15–19 May 2011; Available online: <https://minesparis-psl.hal.science/hal-00711935v1> (accessed on 24 September 2025).
22. Olkkonen, V.; Syri, S. Spatial and Temporal Variations of Marginal Electricity Generation: The Case of the Finnish, Nordic, and European Energy Systems up to 2030. *J. Clean. Prod.* **2016**, *126*, 515–525. [\[CrossRef\]](#)
23. Sacchi, R.; Besseau, R.; Pérez-López, P.; Blanc, I. Exploring Technologically, Temporally and Geographically Sensitive Life Cycle Inventories for Wind Turbines: A Parameterized Model for Denmark. *Renew. Energy* **2019**, *132*, 1238–1250. [\[CrossRef\]](#)
24. Zhu, X.; Wang, S.; Wang, L. Life Cycle Analysis of Greenhouse Gas Emissions of China's Power Generation on Spatial and Temporal Scale. *Energy Sci. Eng.* **2022**, *10*, 1083–1095. [\[CrossRef\]](#)
25. Raadal, H.L.; Gagnon, L.; Modahl, I.S.; Hanssen, O.J. Life Cycle Greenhouse Gas (GHG) Emissions from the Generation of Wind and Hydro Power. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3417–3422. [\[CrossRef\]](#)
26. Kadiyala, A.; Kommalapati, R.; Huque, Z. Evaluation of the Life Cycle Greenhouse Gas Emissions from Hydroelectricity Generation Systems. *Sustainability* **2016**, *8*, 539. [\[CrossRef\]](#)
27. Teffera, B.; Assefa, B.; Assefa, G. Assessing the Life Cycle Environmental Impacts of Hydroelectric Generation in Ethiopia. *Sustain. Energy Technol. Assess* **2020**, *41*, 100795. [\[CrossRef\]](#)
28. Fearnside, P.M. Hydroelectric Dams in the Brazilian Amazon as Sources of Greenhouse Gases. *Environ. Conserv.* **1995**, *22*, 7–19. [\[CrossRef\]](#)
29. Rosa, L.P.; Schaeffer, R.; Santos, M.A. Are Hydroelectric Dams in the Brazilian Amazon significant Sources of Greenhouse Gases? *Environ. Conserv.* **1996**, *23*, 2–6. [\[CrossRef\]](#)
30. Kemenes, A.; Forsberg, B.R.; Melack, J.M. Methane Release below a Tropical Hydroelectric Dam. *Geophys. Res. Lett.* **2007**, *34*, L12809. [\[CrossRef\]](#)
31. Ribeiro, F.M.; Silva, G.A. Life-cycle inventory for hydroelectric generation: A Brazilian case study. *J. Clean. Prod.* **2010**, *18*, 44–54. [\[CrossRef\]](#)
32. Kemenes, A.; Forsberg, B.R.; Melack, J.M. CO<sub>2</sub> Emissions from a Tropical Hydroelectric Reservoir (Balbina, Brazil). *J. Geophys. Res. Biogeosci.* **2011**, *116*, G03004. [\[CrossRef\]](#)
33. Rosa, L.P.; Santos, M.A.; Matvienko, B.; Dos Santos, E.O.; Sikar, E. Greenhouse Gas Emissions from Hydroelectric Reservoirs in Tropical Regions. *Clim. Change* **2024**, *66*, 9–21. [\[CrossRef\]](#)
34. Xia, B.; Qiang, M.; Jiang, H.; Wen, Q.; An, N.; Zhang, D. Phase-Based Externality Analysis for Large Hydropower Projects. *Environ. Impact Assess. Rev.* **2020**, *80*, 106332. [\[CrossRef\]](#)
35. Cusenza, M.A.; Guarino, F.; Longo, S.; Mistretta, M.; Cellura, M. Environmental Assessment of 2030 Electricity Generation Scenarios in Sicily: An Integrated Approach. *Renew. Energy* **2020**, *160*, 1148–1159. [\[CrossRef\]](#)
36. Schomberg, A.C.; Bringezu, S.; Flörke, M.; Biederbick, H. Spatially Explicit Life Cycle Assessments Reveal Hotspots of Environmental Impacts from Renewable Electricity Generation. *Commun. Earth Environ.* **2022**, *3*, 197. [\[CrossRef\]](#)
37. Cho, M.; Qi, J. Determination of Spatial Pattern of Environmental Consequences of Dams in Watersheds. *Land* **2023**, *12*, 2154. [\[CrossRef\]](#)
38. Mahmud, M.; Huda, N.; Farjana, S.H.; Lang, C. A Strategic Impact Assessment of Hydropower Plants in Alpine and Non-Alpine Areas of Europe. *Appl. Energy* **2019**, *250*, 198–214. [\[CrossRef\]](#)
39. Verán-Leigh, D.; Vázquez-Rowe, I. Life Cycle Assessment of Run-of-river Hydropower Plants in the Peruvian Andes: A Policy Support Perspective. *Int. J. Life Cycle Assess.* **2019**, *24*, 1376–1395. [\[CrossRef\]](#)
40. Lazo-Vásquez, D.; Urbina, C.; Rivela, B. On the Potential Environmental Repercussions of Hydroelectricity: A Contribution Based on Life Cycle Assessment of Ecuadorian Hydropower Plants. *Rev. Virtual Quím.* **2021**, *14*, 50–55. [\[CrossRef\]](#)

41. Pehl, M.; Arvesen, A.; Humpenöder, F.; Popp, A.; Hertwich, E.G.; Luderer, G. Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nat. Energy* **2017**, *2*, 939–945. [CrossRef]
42. Briones-Hidrovo, A.; Uche, J.; Martínez-Gracia, A. Determining the net environmental performance of hydropower: A new methodological approach by combining life cycle and ecosystem services assessment. *Sci. Total Environ.* **2019**, *712*, 136369. [CrossRef]
43. Siddiqui, O.; Dincer, I. Comparative Assessment of the Environmental Impacts of Nuclear, Wind and Hydro-Electric Power Plants in Ontario: A Life Cycle Assessment. *J. Clean. Prod.* **2017**, *164*, 848–860. [CrossRef]
44. Song, C.; Gardner, K.; Klein, S.; Souza, S.; Mo, W. Cradle-to-Grave Greenhouse Gas Emissions from Dams in the United States of America. *Renew. Sustain. Energy Rev.* **2018**, *90*, 945–956. [CrossRef]
45. Barros, M.V.; Salvador, R.; Moro, C.; Piekarski, C.M.; Francisco, A.C.; Seixas, F.M.C. Life Cycle Assessment of Electricity Generation: A Review of the Characteristics of Existing Literature. *Int. J. Life Cycle Assess.* **2020**, *25*, 36–54. [CrossRef]
46. Mahmud, M.; Farjana, S.H. Comparative Life Cycle Environmental Impact Assessment of Renewable Electricity Generation Systems: A Practical Approach towards Europe, North America and Oceania. *Renew. Energy* **2022**, *193*, 1106–1120. [CrossRef]
47. Wang, J.; Chen, X.; Liu, Z.; Frans, V.; Xu, Z.; Qiu, X.; Xu, F.; Li, Y. Assessing the Water and Carbon Footprint of Hydropower Stations at a National Scale. *Sci. Total Environ.* **2019**, *676*, 595–612. [CrossRef]
48. Liu, X.; Jiang, Y.; Zheng, X.; Hou, W.; Chen, X.; Xiao, S.; Zhang, X.; Deng, S.; Hao, J.; Luo, H.; et al. Moving towards Co-Benefits of Hydropower: Ecological Efficiency Evaluation Based on LCA and DEA. *Environ. Impact Assess. Rev.* **2023**, *100*, 107208. [CrossRef]
49. Gracey, E.O.; Verones, F. Impacts from Hydropower Production on Biodiversity in an LCA Framework—Review and Recommendations. *Int. J. Life Cycle Assess.* **2016**, *21*, 412–428. [CrossRef]
50. Correia, E.; Calili, R.; Pessanha, J.F.; Almeida, M.F. Definition of Regulatory Targets for Electricity Non-technical Losses: Proposition of an Automatic Model-selection Technique for Panel Data Regressions. *Energies* **2023**, *16*, 2519. [CrossRef]
51. Empresa de Pesquisa Energética (EPE). *Estudo de Viabilidade: UHE de Sinop*; EPE: Brasília, Brazil, 2010. Available online: <https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/estudos-de-viabilidade-tecnica-e-economica-evte> (accessed on 24 September 2025).
52. Empresa de Pesquisa Energética (EPE). *Relatório de Impacto Ambiental (RIMA): UHE de Sinop*; EPE: Brasília, Brazil, 2010. Available online: <https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-247/Rima%20-%20UHE%20Sinop.pdf> (accessed on 24 September 2025).
53. PSR Energy Consulting and Solutions. About PSR. 2025. Available online: [https://www.psr-inc.com/en/who\\_we\\_are/#](https://www.psr-inc.com/en/who_we_are/#) (accessed on 1 September 2025).
54. Ecoinvent Association. *Ecoinvent Database v3.10*; Ecoinvent Association: Zürich, Switzerland, 2023; Available online: <https://ecoinvent.org/> (accessed on 1 September 2025).
55. Ciroth, A.; Di Noi, C.; Lohse, T.; Srocka, M. *openLCA 2.0. Comprehensive User Manual*; GreenDeltaTC: Berlin, Germany, 2019; Available online: <https://www.openlca.org/openlca-manual-update-2/> (accessed on 1 September 2025).
56. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A Harmonised Life Cycle Impact Assessment Method at Midpoint and Endpoint Level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
57. Empresa de Pesquisa Energética (EPE). *Repotenciação e Modernização de Usinas Hidrelétricas*; EPE-DEE-088/2019-r0; EPE: Brasília, Brazil, 2019.
58. Huijbregts, M.A.J. Uncertainty and Variability in Environmental Life-Cycle Assessment. *Int. J. Life Cycle Assess.* **2002**, *173*. [CrossRef]
59. Lloyd, S.M.; Ries, R. Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment: A Survey of Quantitative Approaches. *J. Ind. Ecol.* **2007**, *11*, 161–179. [CrossRef]
60. United Nations Economic Commission for Europe (UNECE). *Carbon Neutrality in Unece Region: Integrated Life-Cycle Assessment of Electricity Sources*; Unece: Geneva, Switzerland, 2022; Available online: [https://unece.org/sites/default/files/2022-04/LCA\\_3\\_FINAL%20March%202022.pdf](https://unece.org/sites/default/files/2022-04/LCA_3_FINAL%20March%202022.pdf) (accessed on 1 September 2025).
61. United States Department of Energy. *National Energy Technology Laboratory (DOE/NETL). Role of Alternative Energy Sources: Hydropower Technology Assessment*; DOE/NETL-2011/1519; DOE/NETL: Pittsburgh, PA, USA, 2012. Available online: <https://www.osti.gov/servlets/purl/1524433> (accessed on 24 September 2025).

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.