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Life Cycle Assessment of Electricity Generation Systems in Angola

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ABSTRACT

Many countries are actively engaged in transforming and diversifying their electrical systems, adopting regulations that promote the integration of renewable energy sources. This process, often referred to as the energy transition, aims to significantly reduce CO_2 emissions, enhance energy efficiency by 2030, and mitigate the impacts of climate change. Temporal assessments of energy transformations provide critical insights into the consumption capacity and potential of primary energy sources. These evaluations enable the identification and prediction of future trends, offering a framework to understand the consequences and opportunities associated with energy transitions. Such insights facilitate the maximization of positive outcomes while minimizing or mitigating adverse effects. This study aims to assess the impact of energy sustainability in Angola's electrical system by considering social, environmental, and economic dimensions. The methodology utilized in this work is based on a life cycle assessment (LCA) approach to evaluate Angola's energy system comprehensively. This includes all stages, from primary energy sources to the final disposal phase, represented by CO_2 emissions. Computational tools for LCA were employed to process data and generate detailed results. The analysis facilitated the identification of trends within the energy sector, enabling the development of strategic recommendations to improve the efficiency and sustainability of Angola's energy infrastructure, with a focus on enhancing the electrical grid and its associated systems. The study results reveal critical trends in Angola's energy sector, highlighting areas for improvement in efficiency and sustainability across the energy value chain. Strategic recommendations were developed to optimize Angola's energy infrastructure, emphasizing advancements in the design, operation, and modernization of the country's electrical grid and associated systems. These improvements aim to reduce environmental impacts, enhance energy reliability, and support the transition to a more sustainable and resilient energy framework. Thus, the sustainability of Angola's electricity system was evaluated from social, environmental, and economic perspectives, leveraging Life Cycle Analysis to consider every stage—from primary energy sources to generation, transportation, distribution, and final disposal—highlighting the CO_2 emissions that contribute to climate change.

Keywords: Life Cycle Analysis, Flow of Energy, Electrical Sustainability, Angola
JEL Classifications: Q28, Q32, Q52

1. INTRODUCTION

The energy sector is a fundamental pillar for the sustainable development of society, playing a crucial role in driving economic growth and supporting industrial activities while meeting basic human needs. As a result, it is recognized as one of the key drivers of sustainable development (Miller and Spoolman, 2021). However, energy conversion and consumption are often linked to significant social, environmental, and economic challenges, including climate change, escalating living costs, and threats to energy security (World Bank, 2023).

In Angola, ensuring a stable and adequate energy supply has become an increasing concern. Over the past decades, substantial investments have been made to expand electricity distribution and transmission capacity (ANGOP, 2025). The nation's rapid demographic growth and economic development have significantly increased the demand for electrical energy for both domestic use and industrial purposes (World Bank, 2023). However, electricity generation in Angola frequently results in pollutant emissions that negatively impact ecosystems and human health (ISO, 2006).

This study employs the principles of life cycle assessment (LCA) to evaluate the sustainability of Angola's electricity production system, with a particular focus on the environmental impacts of energy transformation processes. According to ISO 14040 (2006), LCA provides a structured framework for assessing the environmental impacts across the lifecycle of energy production. Due to the limited availability of data on the transportation and distribution phases, the analysis is centered primarily on the energy production stage. By assessing historical environmental impacts and identifying trends, this research aims to provide insights into the sustainability of energy production processes in Angola, contributing to more reliable and informed decision-making for sustainable energy development.

Sustainability and environmental impacts of energy systems, particularly renewable energy technologies, have been extensively studied. Kiss et al. (2020) conducted an environmental assessment of future electricity mixes, integrating hourly economic models with life cycle assessment (LCA) to evaluate the sustainability of energy systems. Their findings emphasized the critical role of renewable energy sources in reducing environmental impacts.

Similarly, Miguel and Cerrato (2020) performed a life cycle sustainability assessment of Spain's electricity mix, demonstrating the environmental benefits of transitioning to renewable energy sources. Their study showed that wind and solar energy systems significantly reduce greenhouse gas emissions compared to fossil fuel-based systems.

The role of renewable energy in addressing global energy challenges has also been widely explored. Santoyo-Castelazo et al. (2021) analyzed the life cycle environmental impacts of electricity generation in Mexico, emphasizing the need for cleaner energy technologies to achieve sustainability goals. Their work provided a framework for policymakers to prioritize investments in renewable energy.

In the context of developing countries, OSAA (2024) examined global air pollutant emissions and their economic drivers, highlighting the potential of renewable energy to mitigate energy poverty and environmental degradation. This study underscored the importance of international cooperation in promoting renewable energy adoption.

Recent advancements in LCA methodologies have also been a focal point of energy research. Finkbeiner (2014) discussed the evolution of life cycle sustainability assessment, emphasizing its significance in evaluating the environmental impacts of energy systems. Guinée et al. (2011) provided a comprehensive review of the past, present, and future of LCA, offering a robust framework for sustainable energy planning.

The environmental impacts of energy systems remain a central theme in energy research. Chen et al. (2018) explored the environmental costs associated with power station development, while Doney et al. (2020) modelled the effects of acidification on ecosystem services, highlighting the interconnectedness between energy systems and environmental health.

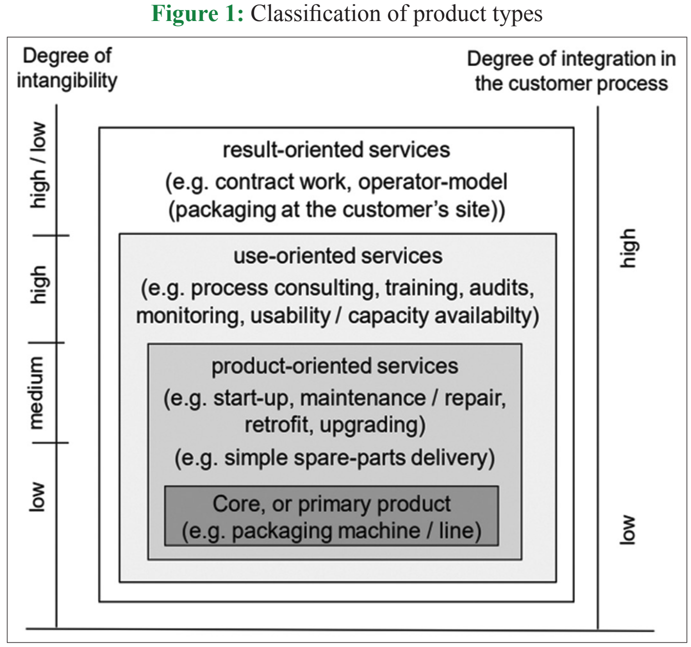
1.1. Concept of a Product Life Cycle

A product is defined as any outcome generated from work or activities within a process. From a physical standpoint, products can be categorized as either tangible or intangible. Depending on their intended purpose, a product represents the result of a process specifically designed to meet customer needs. Both tangible and intangible products can be conceptualized as integral components of a fundamental system, resembling processes within a traditional industrial framework (Schonsleben, 2019; Kotler and Keller, 2020; Silva et al., 2025).

Resource-oriented services, which are typically intangible, significantly influence a product's value chain through services such as consultations, training, audits, monitoring, and system usability enhancements. These services play a crucial role in adding value, ensuring functionality, and improving the efficiency of the associated products (Vargo and Lusch, 2004). Additionally, the incorporation of resource-oriented services into industrial frameworks has been shown to foster innovation, enhance customer satisfaction, and promote sustainable development (Prahalad and Ramaswamy, 2004; Porter and Heppelmann, 2015). Figure 1 illustrates the structure of industrial services, highlighting their dependency on the level of intangibility and their degree of integration within the broader process.

Product life cycle (PLC) management seeks to optimize the entire production chain, from conception to disposal, in order to enhance the sustainability of products across social, environmental, and economic dimensions (ISO, 2006). According to ISO 14040, the

Figure 1: Classification of product types



Source: (Schonsleben, 2019)

international standard for Environmental Management, which provides the principles and framework for Product Life Cycle Assessment (LCA), the PLC comprises four key phases (ISO, 2006; De Oliveira et al., 2025).

The first phase involves the precise definition of the product, along with the establishment of the study's objectives and scope. This phase outlines the structure of the analysis, identifies the goals for the subsequent stages, and defines the data quality requirements, selection of parameters for impact assessment, and interpretive possibilities in the context of product evaluation (Baumann and Tillman, 2004). Due to the limited availability of data on all segments of the Angolan electric power system (SEP), this study focuses on the production and consumption of electrical energy. By examining the beginning and end of the SEP value chain, this approach provides valuable insights into the system's sustainability and efficiency.

1.2. Life Cycle Inventory

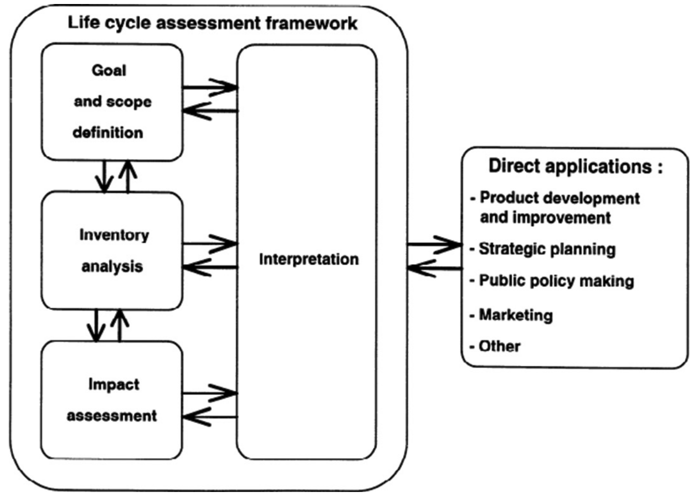
In inventory analysis, material and energy flows are identified and recorded throughout their entire lifecycle. As a preliminary step, the process structure is modeled to provide a foundation for data collection and analysis (Huppes and Ishikawa, 2005). Material and energy flows are quantified based on the inputs and outputs of each subprocess within the defined system boundaries (Heijungs et al., 2003). The interactions between system modules and their environment are captured through the interconnection of all subprocesses, enabling the construction of a comprehensive mass and energy balance, which serves as the inventory for the entire system (Finkbeiner, 2014). All material and energy flows crossing the system boundaries are documented in physical units, ensuring consistency and accuracy in the analysis (ISO 14040, 1997; Richards et al., 2011).

1.3. Life Cycle Impact Assessment

Impact assessment involves evaluating the material and energy flows identified in the inventory analysis to estimate their environmental effects (Baumann and Tillman, 2004). This phase enables the recognition, synthesis, and quantification of the potential environmental impacts associated with the analyzed systems, providing critical insights for a comprehensive evaluation (Guinée et al., 2011). Research institutions worldwide continue to refine and develop more accurate methodologies for this type of analysis (Suh, 2004). The first international consensus on impact assessment was established in ISO 14042, which outlines key principles and methodologies, building upon the framework provided in ISO 14040 (ISO 14042, 1999).

As a result of the life cycle assessment (LCA) analysis, strategic plans should be developed to enhance product sustainability by improving production efficiency and mitigating environmental and social impacts (Norris, 2001). These efforts aim to strengthen the value chain of the electricity sector, spanning production, consumption, and energy disposal, including CO_2 emissions management (UNECE, 2021). The individual steps involved in assessment and impact evaluation are outlined in Figure 2, which illustrates the structural model of the LCA management platform (ISO 14044, 2006).

Figure 2: Phases of an life cycle assessment



Source: (ISO 14040, 1997)

The international standard ISO 14042 (1999), which governs Environmental Management in the context of life cycle impact assessment (LCIA), provides a modular hierarchy for evaluating the most prevalent impacts associated with a product's Life Cycle (ISO 14042, 1999). This standard is designed to assess and interpret the potential environmental effects of products, processes, or services, considering their entire life cycle—from raw material extraction to disposal. The LCIA phase identifies and quantifies environmental impacts, allowing decision-makers to prioritize mitigation strategies based on the severity and scope of the identified effects.

The impact categories are defined for consideration in the ISO 14042 framework: (a) Depletion of renewable resources is focuses on the consumption of resources that can be naturally replenished, such as biomass, water, and certain energy sources. Overuse can lead to depletion, affecting future availability and ecological balance (Bringezu et al., 2003); (b) Global warming examines the potential for products or processes to contribute to climate change by emitting greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases trap heat in the atmosphere, leading to rising global temperatures and associated environmental impacts (IPCC, 2014); (c) Human toxicity and eco-toxicity effects of chemicals or pollutants on human health and ecosystems. Human toxicity refers to potential harm to human populations through exposure to harmful substances, while eco-toxicity considers the broader environmental consequences, including harm to biodiversity and ecosystem functions (Van de Meent, 1993); (d) Acidification addresses the potential for acid deposition, which occurs when emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) react with water vapor in the atmosphere, forming acids that can damage soil, water systems, and vegetation (Doney et al., 2020).

Thus, the Figure 3 illustrates the sequential analysis across the phases of a product's Life Cycle, emphasizing these impact categories. The life cycle stages—such as raw material extraction, manufacturing, transportation, use, and disposal—are systematically evaluated to identify the specific environmental consequences at each stage. This process enables companies and researchers to identify areas where interventions can reduce environmental burdens, enhancing sustainability practices in product development and production.

Additionally, ongoing research into Life Cycle Impact Assessment methods continues to refine the quantification of environmental impacts, incorporating new scientific insights and technological advancements. Thus, the development of the ReCiPe method integrates multiple environmental impact categories into a single framework, offering a more comprehensive and scientifically accurate assessment (Goedkoop et al., 2009).

As a result of the impact analysis, strategic plans should be proposed at the conclusion of the evaluation process to improve the product, aligning it with sustainability and efficiency objectives. Alternatively, the inventory data can be used to develop a new product, optimizing its environmental and social impacts (ISO 14042, 1999). In this research, electrical energy consumption in Angola was chosen as the intangible product for evaluation, characterized by its use-oriented nature.

1.4. Overview of the Angolan Energy Chain

The energy chain encompasses the flow of energy from primary energy production to final energy consumption. The Electrical Power System (SEP), illustrated in Figure 4, is composed of integral functions and elements, subdivided into large blocks: Generation, transmission, and distribution. These blocks are described as follows: (a) Generation involves the production of electrical energy at power plants, where various forms of energy (such as kinetic or thermal) are converted into electricity. (b) Transmission refers to the process of conveying electrical energy from generation facilities to distribution networks through high-voltage transmission lines and step-down transformers. (d) Distribution involves the delivery of electrical energy from the transmission system to end users. In 2018, end consumers accounted for 51% of total consumption, with this figure increasing to 54% in 2020, demonstrating a growing impact in the sector.

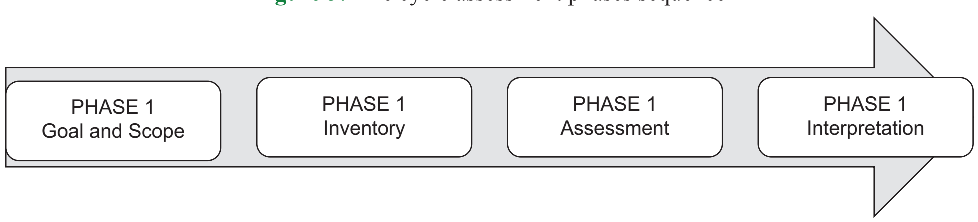
According to the Ministry of Energy and Water (MINEA, 2023), Angola's current electrification rate is approximately 30%. The country's hydroelectric energy potential is estimated at 18.2 GW, with around 30% of this capacity currently in use. The total installed power in Angola exceeds 4.889 GW, distributed across the following production types: (a) Hydroelectric; (b) Thermal; (c) Natural gas (d) Renewable energy. This data is further detailed in Table 1 (MINEA, 2023).

In 2023, the energy consumption in the domestic sector is approximately 1.2 MWh per person, with an estimated increase to 1.5 MWh per person by 2025. Per capita electricity consumption in 2022 was 408 kWh. According to the 2024 MINEA report, Angola's water usage includes 85 substations, with a network loss of approximately 14%. This results in the following consumption distribution: 45% for domestic use, 32% for services, and 9% for industrial use.

1.5. Electrical Energy Life Cycle Analysis Tools

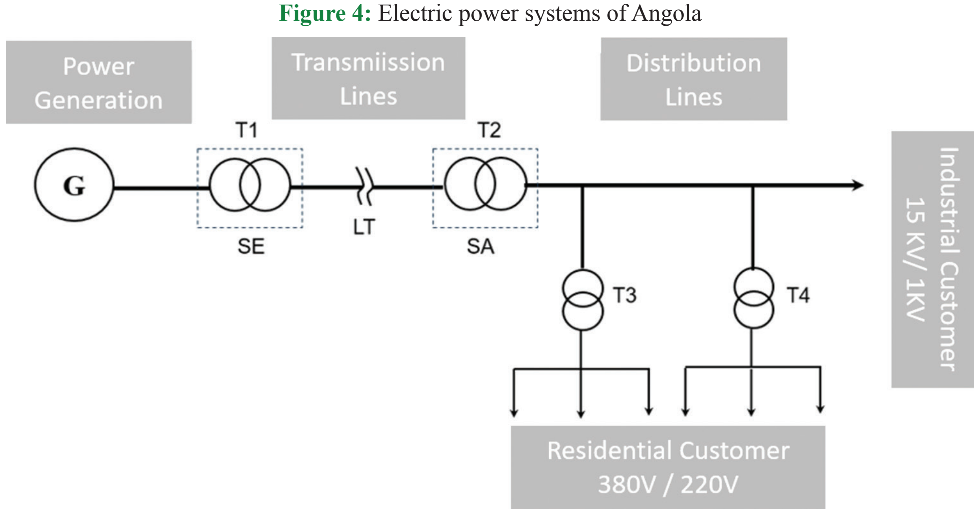
There are several product life cycle management (LCA) tools. The following computational tools were used in this work:

Figure 3: Life cycle assessment phases sequence



Source: The author (2025)

Figure 4: Electric power systems of Angola



Source: The author (2025)

Table 1: Capacity of electricity production mix in Angola

Power generation plant	Capacity power installed	Weight (%)
Hidroelectric plant	3.005 GW	61
Termal sources	1.866 GW	31
Natural gas	0.375 GW	7
New renewables	0.063 GW	1

Source: (MINEIA, 2023)

(a) OpenLCA version 2.3 (OpenLCA, 2024) and; (b) PLM from the OpenSource Odoo platform (Cybrosys Technologies, 2008). In general, a product Life Cycle management tool encompasses the data entry module (MED) that defines and configures the parameters of each subproduct of the main product, as well as the databases associated with a given industrial product. On the other hand, it also incorporates the product module (MP) characterized as the functional and structural representation of the product, obtained with the defined parameters, and with a list of the product BOM (bill of material). Furthermore, it contains the impact analysis module used to evaluate the assumptions of the LCA analysis and the method used by the computational tool to develop the product. Finally, the visualization and interpretation module, used as an LCA analysis tool and makes it possible to visualize and present data, to extract information and knowledge that result in the understanding of the product or process to better enhance the positive aspects and mitigate the negative aspects, results of data interpretation.

2. METHODOLOGY

When evaluating the Life Cycle of a product, it is essential to account for the specific characteristics—whether material or immaterial—of each product, considering the technological aspects involved at each stage. In the case of electricity, the primary challenge lies in assessing the full scope of its life cycle, which includes generation, production, and distribution to the end user. These processes are consistent across all types of electricity generation, whether fossil-based, renewable, or nuclear. However, the life cycle assessment (LCA) presented in this study does not include the electricity distribution phase, due to the unavailability of comprehensive data for this part of the supply chain. Additionally, the environmental impacts associated with the construction of electricity generation plants and transmission lines (TL) have been excluded from the assessment, again due to data limitations. Thus, the methodology developed for conducting the life cycle analysis (LCA) of electricity consumption consists of five distinct and structured stages:

Conception for LCA design of energy consumption: This initial stage focuses on the collection of bill of materials (BOM) data that pertains to electricity generation and consumption, with a particular emphasis on hydropower as a primary energy source. The BOM data is gathered from established international databases, such as countryeconomy.com, and supplemented by local data from the ministry of energy and water (MINEA). The objective here is to establish the foundational framework for the LCA by linking the generation, consumption, and environmental impacts of electricity. This stage ensures that the boundaries of the study are clearly defined, taking into account regional specifics and the local energy mix.

Development of the LCA of electricity consumption: This phase involves detailed configuration and modeling within the LCA platform, focusing on energy input and output processes. The platform is designed to accommodate various energy flows, such as the inflow of hydropower and its conversion to electricity, as well as the associated energy losses during transmission. It also involves the integration of the collected BOM data, ensuring that energy use is accurately captured across different sectors. The development of the LCA model allows for an in-depth representation of the energy system, ensuring that all relevant environmental impacts are accounted for across the system.

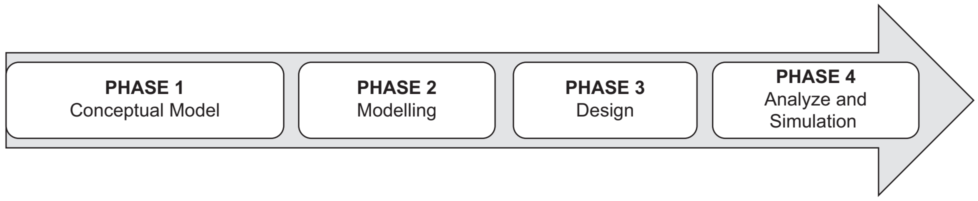
Design of the energy consumption LCA Platform: In this stage, the focus shifts to the design and structuring of the LCA platform itself. This involves creating a user-friendly interface that can handle the large volumes of data associated with energy consumption across multiple phases. The design incorporates various functionalities that facilitate the input of diverse data types, including energy generation and consumption patterns, and allows for the customization of data entry for different scenarios. Additionally, it ensures that the platform can accommodate future updates and data from additional energy sources as they become available.

LCA Analysis and Simulation Functionalities: Once the platform is designed and configured, this stage involves running simulations and analyzing the environmental impacts of electricity consumption. The LCA simulations are based on the input data and models developed in the previous stages, enabling the evaluation of potential environmental impacts, such as CO_2 emissions, water consumption, and resource depletion. The analysis focuses on the life cycle of electricity, from generation through to end use, and includes the assessment of energy efficiency, the carbon footprint, and the sustainability of the energy systems. This stage also provides the necessary tools for sensitivity analysis, allowing for the exploration of various scenarios and their potential environmental outcomes.

Optimization and Reporting: The final stage focuses on synthesizing the results of the LCA analysis and developing strategies to optimize the electricity consumption process. The results from the LCA platform are used to identify areas where environmental impacts can be reduced, such as through the adoption of more efficient technologies or by shifting to cleaner energy sources. This stage also involves generating detailed reports that communicate the findings of the LCA to stakeholders, policymakers, and the public. These reports highlight key opportunities for improving the sustainability of the energy system, providing a clear roadmap for future action.

The Figure 5 illustrates the functional process flow of the LCA evaluation platform, highlighting the stages from the primary energy source to the end consumer. The figure demonstrates how the LCA framework integrates the data from each of the five stages, enabling a comprehensive understanding of the environmental impacts of electricity consumption. By providing a detailed, step-by-step overview, Figure 5 illustrates the complexity of the electricity life cycle and the potential for reducing its

Figure 5: Process flow for the development of the life cycle assessment



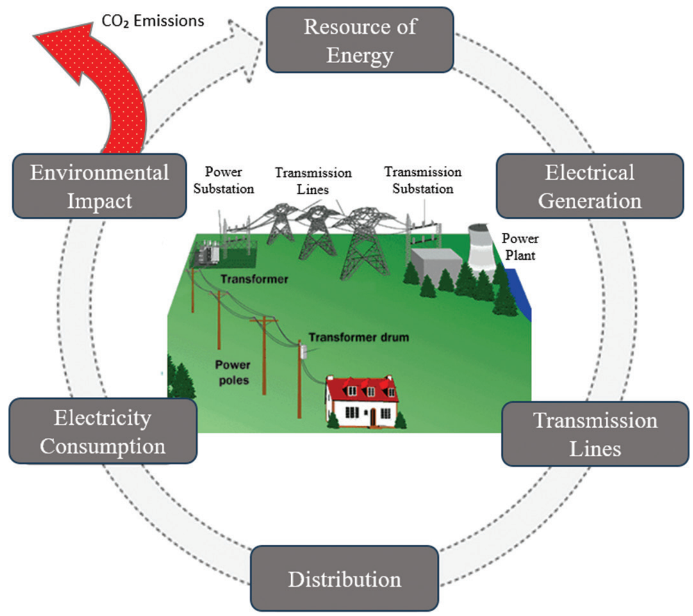
Source: By the authors (2025)

environmental footprint through informed decision-making and technological innovation.

Data on Angola's hydroelectric potential, generation capacity, and energy consumption from 1980 to 2022 were collected from the MINEIA reports (2023) and countryeconomy.com, which compiles information from 19 international databases across various sectors, including energy. The data collection specifically focused on energy generation and final consumption, as comprehensive data on the transportation and distribution segments of the energy sector were unavailable, hindering a full assessment of the entire energy value chain.

The primary objective of life cycle assessment (LCA) of electricity is to evaluate opportunities for improving the "product" within the energy system chain. The goal is to present strategic decisions or plans that, when implemented, would enhance the electricity value chain. This assessment takes into account the social, environmental, and economic dimensions of sustainability, focusing on consumption demand, CO_2 emissions, and the utilization of available primary energy resources in Angola, as detailed in Figure 6 (Kiss et al., 2020).

Figure 6: Life cycle assessment of electrical system



Source: By the authors (2025)

3. RESULTS AND DISCUSSION

Energy generation relies on assessing available sources, both renewable and non-renewable, with the efficiency of these sources being crucial in determining the sustainability of the system. This includes considerations of CO_2 emissions and the consumption of natural resources, as energy efficiency can reduce the environmental footprint and optimize resource utilization.

Transmission and distribution networks, however, are associated with energy losses, which represent a significant challenge. These losses can be mitigated through technological innovations such as smart grids and modernized infrastructure. Reducing these losses increases the overall efficiency of the energy system. Energy use patterns vary according to cultural, economic, and technological contexts, factors that directly influence energy demand. Consequently, the durability and energy efficiency of products consumed daily determine their contribution to overall sustainability. The end-of-life phase of products and energy systems requires careful planning to minimize environmental impacts. Recycling and energy recovery should be prioritized to reduce waste and conserve natural resources.

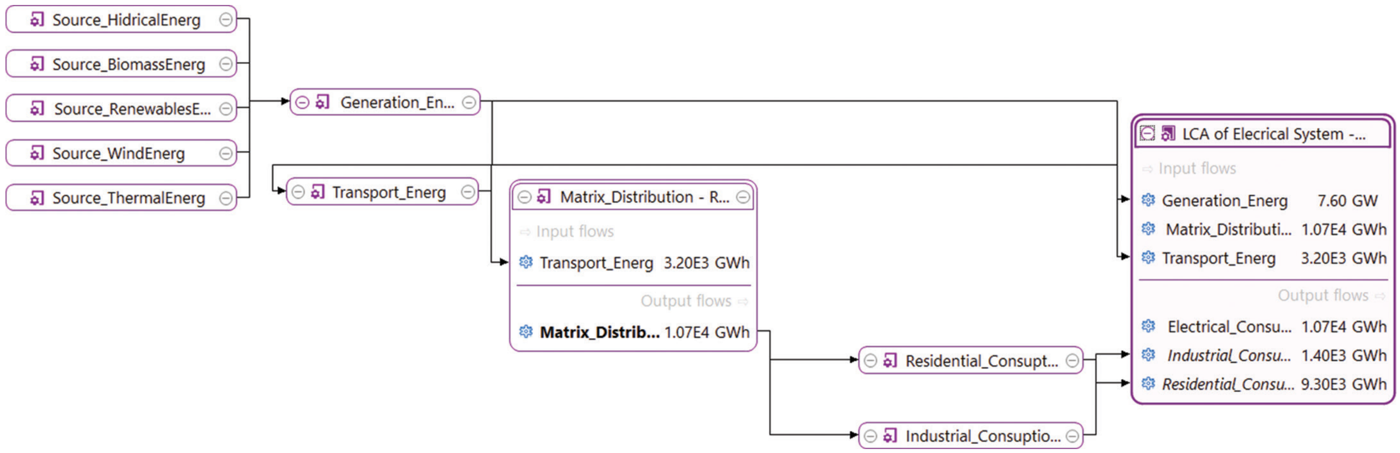
Energy tariffs also play a key role in ensuring accessibility and equity in consumption. Sustainable tariff policies are needed to encourage the adoption of renewable sources and promote energy efficiency. Moreover, energy generation and consumption are closely linked to greenhouse gas (GHG) emissions, water consumption, and pollution. Mitigation strategies, such as the transition to clean energy, can significantly reduce these impacts. This transition requires the adoption of solar, wind, and other renewable sources to reduce CO_2 emissions and contribute to decarbonization, necessitating robust planning for grid integration.

These challenges underscore the need for advanced research into energy storage technologies, such as high-capacity batteries, to balance supply and demand in renewable systems with intermittent generation. Encouraging conscious energy consumption and educating the public about the impacts of energy use is essential to reducing demand and fostering more sustainable choices. This requires the implementation of policies that promote energy efficiency and emission reductions, fundamental for ensuring a sustainable energy life cycle with economic, social, and environmental benefits.

3.1. Development of the Electricity Life Cycle Model

In order to develop the product's life cycle model, the following characteristics of the process were taken into account, from generation to consumption and disposal of electricity, by means of greenhouse gas emissions. Therefore, the definition of the

Figure 7: Breakdown structure of the electrical system



Source: By the authors (2025)

Angolan Electricity life cycle took into account all the elements and processes that make up the Angolan SEP:

a. Primary energy sources, which enter into an electricity generation process as a tangible product;
b. Energy generation, transportation and distribution processes, which receive energy from the Primary source, transform it, transport it and distribute it to consumers at the end of the SEP, treated as by-products, an intangible product;
c. Domestic and industrial consumers who consume electricity in the distribution network;
d. The emission of greenhouse gases CO_2, which are released into the environment, both in generation and consumption, as forms of energy disposal.

In this way, the life cycle model for electricity in Angola follows the life cycle assessment method, taking into account the analysis of the improvement of the energy sector in harmony with the objectives of social, environmental and economic sustainability.

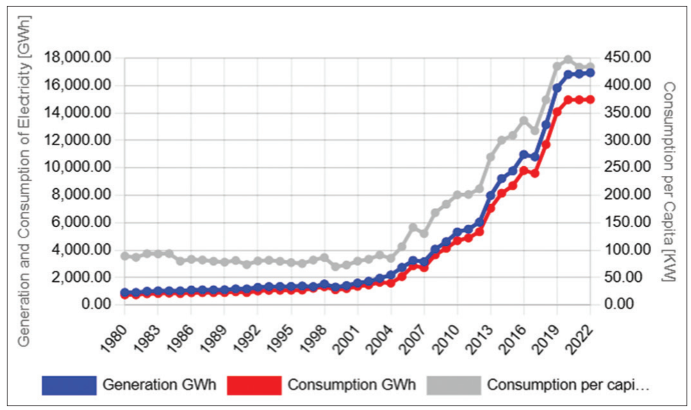
A model has therefore been proposed to assess impacts in the various categories they cover:

a) A special focus on the natural resources involved in electricity production;
b) Assess the environmental impacts in terms of greenhouse gas emissions, CO_2, at the end of the energy life cycle;
c) Evaluate the social impacts in terms of the relationship between electricity demand and consumption in Angola.

To develop the flow of electricity in Angola, the OpenLCA platform was used, which is suitable for the type of intangible product, considering the number of industrial product databases that are supported, with complete data on characteristics and suppliers, which made it possible to draw the Breackdown of the physical and functional structure of the product illustrated in Figure 7.

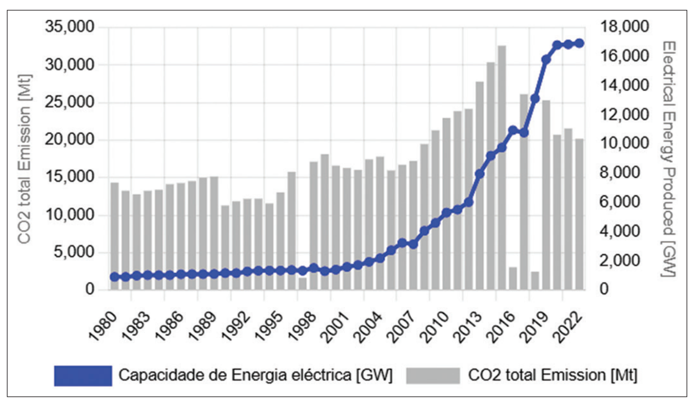
The OpenLCA platform defines 3 main types of products: (a) Elementary Flow: Represents the raw material that enters the process directly, without the need for human transformation; (b) Waste: Substance or object to be discarded, which is intended to be kept in the product, CO_2 emissions and; (c) Product: A good, service, tangible or intangible product processed, or produced.

Figure 8: Assessment of energy efficiency



Source: By the authors (2025)

Figure 9: Environmental impact of Angola electricity

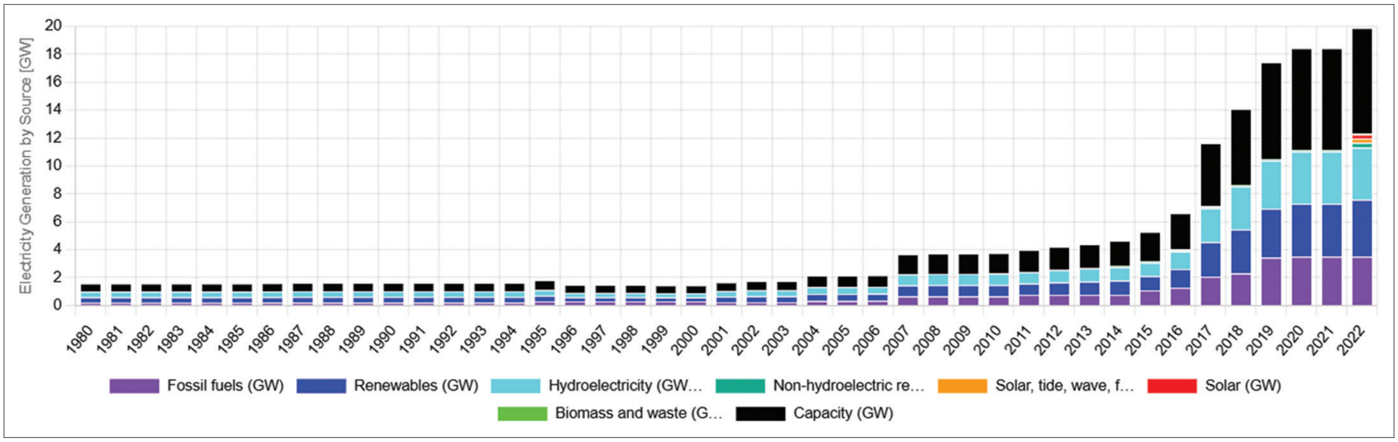


Source: By the authors (2025)

3.2. Life Cycle Analysis of Electricity

In the evaluation phase, data was collected on installed and consumed electrical power, as well as electricity sources from 1980 to 2022. This data was extracted from international databases and compared with information from MINEA for validation (Alldatanow, 2024). Using the data obtained from the electricity

Figure 10: Assessment of Angola's electricity generation by source



Source: By the authors (2025)

sector, the Odoo tool was employed to analyze the Life Cycle of electricity in Angola. In the Life Cycle analysis of electricity, the product architecture was initially defined, describing the corresponding subproducts at each phase to build the complete inventory of electricity, or bill of materials (BOM), using the Odoo PLA module. With the definitions of Angola's energy chain, dashboards were created to visualize and analyze the following impacts:

3.2.1. Social Impact

The social impact of electricity was assessed by comparing the demand and consumption of electricity from 1980 to 2022, as shown in Figure 8. From the LCA analysis, it was observed that Angola's installed energy capacity is lower than its consumption, despite the existence of areas without electrification. The analysis indicates that the deficit is not related to energy production but rather to distribution and access issues in certain regions.

3.2.2. Environmental Impact

The environmental impact of electricity in Angola was evaluated by comparing CO_2 emission trends from 1980 to 2022, as illustrated in Figure 9. Despite the growth in electricity consumption and installed capacity, CO_2 emissions have not risen proportionally. According to MINEIA (2023), Angola's CO_2 emissions remain among the lowest in Southern Africa. In fact, Angola is ranked 59th among the world's greenest nations, highlighting its relatively low environmental impact in comparison to other countries (MINEIA, 2023).

3.3. Electrical Life Cycle Assessment and Sustainability

To evaluate the impact of electricity on energy sustainability, a graph was developed (Figure 10) that visually illustrates critical factors, including energy consumption, CO_2 emissions, and installed capacity. This provides a comprehensive overview of how electricity generation affects sustainability in Angola.

The impact on electrical sustainability in Angola was assessed by analyzing the contribution of each primary source of electricity to the generation process from 1980 to 2022. The life cycle assessment (LCA) of sustainability revealed that Angola has considerable energy potential, with hydroelectric power being the dominant source of electricity generation, accounting for about 60% of the total installed capacity. This is particularly significant given the country's vast water resources, which could be better harnessed for energy production.

Hydroelectric potential in Angola is estimated at around 18 GW, which represents a significant opportunity for future expansion in renewable energy capacity. However, despite this potential, the country has only utilized a fraction of its hydroelectric resources, with significant untapped capacity remaining. This underscores the importance of strategic planning and investment in hydroelectric infrastructure to optimize the use of renewable energy, reduce dependency on fossil fuels, and improve overall energy sustainability in the country.

The LCA results also highlight the critical role of sustainability in shaping Angola's energy future. By focusing on the development of renewable sources like hydroelectric power, Angola can enhance its energy security, mitigate environmental impacts, and contribute to global climate change mitigation efforts. This alignment with sustainable energy goals can further strengthen the country's position as a leader in clean energy generation in southern Africa.

4. CONCLUSION

The global transition towards renewable energy underscores the necessity of implementing robust control measures and forecasting the impacts of adopting renewable energy systems. This study assessed the sustainability of Angola's electricity system from social, environmental, and economic perspectives, leveraging Life Cycle Analysis to evaluate the system's processes, from primary energy sourcing to generation, transportation, distribution, and the disposal of energy in the form of CO_2 emissions, which contribute to climate change. This analysis highlights Angola's significant potential for leveraging renewable energy resources while providing actionable insights for improving the efficiency and sustainability of its energy infrastructure. Based on an analysis of data on installed power capacity, energy consumption, and the potential of primary energy sources in Angola's energy sector from 1980 to 2022, the following conclusions were drawn:

i. The increase in electricity consumption and installed capacity in Angola has not significantly contributed to growth in CO_2 emission levels;
ii. The existence of areas with low electrification does not reflect a deficiency in production capacity, as the installed capacity exceeds national consumption;
iii. Approximately, 60% of Angola's energy potential derives from hydroelectric sources, underscoring the importance of diversifying the national energy matrix to enhance sustainability;
iv. Key advantages promoting the optimization of Angola's energy potential include:
    a. The presence of a competitive energy market;
    b. The need to expand and refine energy management strategies;
    c. Support for strategic decision-making in the control and management of the country's electricity system.

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