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Carbon footprint of electricity transmission: insights from a Brazilian case study

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Abstract

Electricity grids play a crucial role in electricity systems worldwide and will become even more critical as the transition to clean energy advances. In this regard, reducing greenhouse gas (GHG) emissions associated with electricity transmission is crucial to supporting carbon reduction goals and achieving carbon neutrality in light of the escalating climate concerns. This paper aims to quantify the carbon footprint of transmitting electricity through a case study of a transmission line in Brazil (BR-TL). For this purpose, we developed a comprehensive electricity transmission scenario using the ANAREDE software. Additionally, our analysis is derived from data obtained through both primary and secondary sources concerning relevant inputs and outputs considering the construction, operation, and decommissioning stages. As a result, transmitting electricity through the BR-TL transmission line results in 10.89 $gCO_2eq.$ per kWh delivered. Notably, the operation stage is responsible for over 67% of these GHG emissions, predominantly due to energy losses during electricity transmission and associated with the electrical substation transformers. Our results also highlighted the relevance of the construction stage, contributing more than 32% of the carbon footprint, which is mainly linked to GHG emissions resulting from land use change. These findings offer valuable insights for future electricity transmission infrastructure development, aligning with national climate targets and supporting global decarbonization efforts.

Keywords: Electricity transmission, transmission line, electricity, carbon footprint, climate change

INTRODUCTION

Electricity grids are vital to electricity systems worldwide and will be even more essential as the transition to clean energy advances[1]. Meeting countries' energy and climate targets requires expanding renewable energy generation and electrification in transportation, heating and cooling systems, and hydrogen production[1,2]. According to the International Energy Agency (IEA)[1], wind and solar photovoltaic (PV) will drive more than 80% of the growth in global power capacity over the next two decades. This expansion entails upgrading transmission and distribution (T&D) grids to connect remote renewable resources[2,3], including solar PV power plants in desert areas and offshore wind turbines located far from major demand centers, such as urban and industrial zones[1].

In Brazil, the electricity grid has shown to be even more pivotal due to its continental territorial expanse[4,5] and the complexity of its huge hydro-thermo-wind electricity generation and transmission system, primarily consisting of large hydropower plants[6]. The extensive transmission grid in the country spans more than 175,000 kilometers[7], connecting regions with high electricity generation, such as the North, to the consumer centers, mainly in the Southeast[5].

As the Ten-Year Energy Expansion Plan (PDE as in its Portuguese acronym)[7] states, the Brazilian electricity generation expansion, mainly through wind and solar PV energy sources, will lead to a continuous expansion of the transmission grid in the country[8] that should surpass the 200,000-kilometer mark by 2031[7]. At the same time, while there are several technical challenges and barriers to the broader adoption of electric vehicles (EVs) in Brazil, the Energy Research Office (EPE, from its Portuguese acronym) expects that the share of EVs - which includes hybrid and plug-in hybrid vehicles - in the national fleet will increase from less than 1% today to just over 8% by 2034, totaling approximately 4 million vehicles[9]. Without a doubt, this increase in EV adoption will significantly impact electricity demand, as well as T&D grids[9,10].

When looking closer at the future of electricity systems, it is interesting to note that electricity grids will change how they operate[2]. At the same time, they will continue to rely on traditional components such as power lines, cables, transformers, and electrical substations, which are made mainly of metals like copper and iron[1,2]. Hence, understanding the role of upgrading and expanding electricity grids in developing a sustainable energy transition means deeply understanding the environmental impacts of the current electricity grids[2,3]. In this sense, life cycle-based tools are particularly appropriate as they allow for addressing sustainability issues at each stage of products' and services' life cycles. This approach offers a comprehensive view of the electricity supply chain, highlighting and avoiding the burden-shifting between life cycle stages, impact categories, processes/activities, or geographical areas[11].

From this perspective, electricity T&D have received too little attention[1-3,12-14]. While there is a growing body of scientific literature on the life cycle environmental impacts of electricity generation, few studies address electricity T&D[2,3]. This discrepancy stems from the perception that the environmental impacts of electricity grids are small since they are generally lower than those of electricity generation[3,13]. However, it is important to recognize that they can influence the environmental performance of the entire electricity supply chain and, therefore, are not negligible[3]. Consequently, reducing greenhouse gas (GHG) emissions associated with electricity T&D is crucial to supporting carbon reduction goals and achieving carbon neutrality in light of the current climate concerns[1,14].

With this in mind, Jorge *et al.*[13,15] conducted a comprehensive study on the Life Cycle Assessment (LCA) of electricity T&D, divided into two parts. The first part[13] focused on power lines and cables, while the second[15] addressed transformers and electrical substation equipment. In another study, Jorge and Hertwich[2] evaluated the environmental impacts of Norwegian electricity transmission using the LCA methodology. Additionally, Arvesen *et al.*[3] conducted an LCA on transmitting electricity through different voltage levels in Norway. Turconi *et al.*[12] carried out a life cycle-based study on electricity T&D in Denmark, considering the current and future electricity systems. In recent work, Chen and Ou[16] proposed an innovative methodology for estimating the carbon footprint associated with electricity transmission and transformation equipment. Simultaneously, Li *et al.*[14] investigated GHG emissions within the Chinese electricity T&D sector based on LCA.

These previous studies address the environmental impacts of the electricity T&D life cycle in various contexts, highlighting that these impacts, particularly those related to energy losses, are not negligible. Although the contribution of energy losses varies by country due to different factors such as the overall electricity efficiency, the electricity generation mix, and distances from the power plants to the consumption centers[13], there is currently a lack of life cycle-based studies on electricity T&D in Brazil. Therefore, important questions regarding the Brazilian electricity grid need to be answered, including estimating the environmental impacts throughout the electricity transmission life cycle, identifying the most impactful processes and components, and assessing the contribution of energy losses considering the country's electricity generation mix.

This paper is part of an ongoing research and development (R&D) initiative at the Brazilian Electric Energy Research Center (CEPEL), commissioned by a company within the Brazilian electricity sector. This project aims to develop a methodology for performing carbon footprint analyses on electricity generation and transmission in Brazil. Within this context, the present paper centers on quantifying the GHG emissions at various stages of transmitting electricity through a case study of a transmission line in Brazil referred to as the BR-TL transmission line.

Unlike previous studies, this paper specifically addresses the life cycle environmental impacts of electricity transmission within Brazil's unique context, characterized by a predominantly renewable electricity generation mix and distinct regional factors. By providing a comprehensive analysis of the carbon footprint of the BR-TL transmission line, the present study not only addresses a critical gap in the existing literature but also offers valuable insights for the future development of electricity transmission infrastructure. This aligns with national climate targets and supports global decarbonization efforts.

METHODS

Carbon footprint

Over the past two decades, various footprints have emerged within the environmental domain, each addressing specific environmental concerns. Despite their diversity, these tools share a fundamental principle: the life cycle approach. They can assess various targets, such as products, services, organizations, locations, and nations[17,18]. The carbon footprint specifically addresses climate change. In this way, it employs a metric measured in CO_2 equivalent (CO_2eq.), which captures GHG emissions throughout a product or service's value chain. This metric reflects the amount of CO_2 that produces an equivalent radiative forcing effect as a specific GHG[17-19].

In the context of electricity transmission, the carbon footprint encompasses the direct and indirect GHG emissions throughout the whole life cycle of the transmission lines, electrical substations, and ancillary facilities[13,15,20]. In other words, this includes GHG emissions associated with their construction, operation, and decommissioning stages. According to ISO 14067[21], a comprehensive carbon footprint analysis is conducted by implementing an LCA framework, which comprises the following steps: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation.

Anarede software

In life cycle-based analyses, energy losses during transmission lines' operation stage contribute significantly to their electricity transmission's environmental performance[2,3,12,14]. These energy losses are influenced by various factors, including the technology and efficiency of the equipment used in the electricity transmission system, the distances from the power plants to the electricity consumption centers, and the electric current passing through the transmission line[1,13,15]. Given the size and complexity of the Brazilian Interconnected System (SIN as in its Portuguese acronym), it is essential to develop an operating scenario for analyzing the electricity transmission systems throughout their useful life, considering their energy flows and losses, as well as the electricity delivered during their operation.

In this context, the Analysis of Electrical Power Systems in Steady State (ANAREDE)[22] software is particularly interesting and widely used in Brazil. Developed by CEPEL, ANAREDE encompasses a suite of computational applications designed to analyze electricity systems. In addition to power flow, this software has modules for network equivalent, contingency analysis, voltage and flow sensitivity analyses, continuous power flow, analysis of recomposition corridors, automatic transmission margin calculation, and static security assessment. ANAREDE's capabilities are regularly updated to meet the requirements of simulating the SIN. The analysis of the ANAREDE's outcomes provides a clear accounting of energy losses and energy delivered based on the operational time of the electricity transmission system in each static operating scenario considered for the SIN. In this sense, a time-varying scenario must also be prepared, considering the Brazilian characteristics concerning the seasonal variations in both electricity demand and supply[22].

Case study

BR-TL presentation

BR-TL is a 230 kV transmission line located in the central-west region of Brazil. This AC transmission line has operated since 1984 and uses overhead cables supported by 307 delta-type transmission towers to transmit electricity between two electrical substations approximately 112 km away, following a grid-grid pattern. Substation 01 (S01) is a step-up electrical substation with 200 MVAr, while Substation 02 (S02) is a step-down electrical substation with 650 MVAr. Therefore, the electricity transmission system under study encompasses the BR-TL transmission line and the S01 and S02 substations.

For the infrastructures of the electricity transmission system, the system boundary is defined from cradle to grave, including the construction, operation, and decommissioning stages. As the electrical substations also serve other transmission lines, only a portion of their infrastructure is allocated to the electricity transmission system based on their nominal reactive powers dedicated to it. Specifically, this system is associated with 0.15 (30 MVAr/200 MVAr) of the S01 infrastructure and 0.05 (30 MVAr/650 MVAr) of the S02 infrastructure. For electricity, only its transmission is considered. Figure 1 illustrates the system boundary established to calculate the carbon footprint of transmitting electricity through the TL-BR transmission line.

The functional unit established for assessing the carbon footprint associated with electricity transmission via the BR-TL transmission line is the delivery of 1 kilowatt-hour (kWh) of electricity to the local distribution grid [see Figure 1]. Furthermore, this analysis is supported by developing an electricity transmission scenario for the system and gathering relevant data from primary and secondary sources. While the former corresponds to the BR-TL transmission line’s team and other relevant stakeholders, the latter includes the Ecoinvent 3.8 database[23], the Emisfera Platform[24], the ReCiPe 2016 method[25], and the MapBiomas[26]

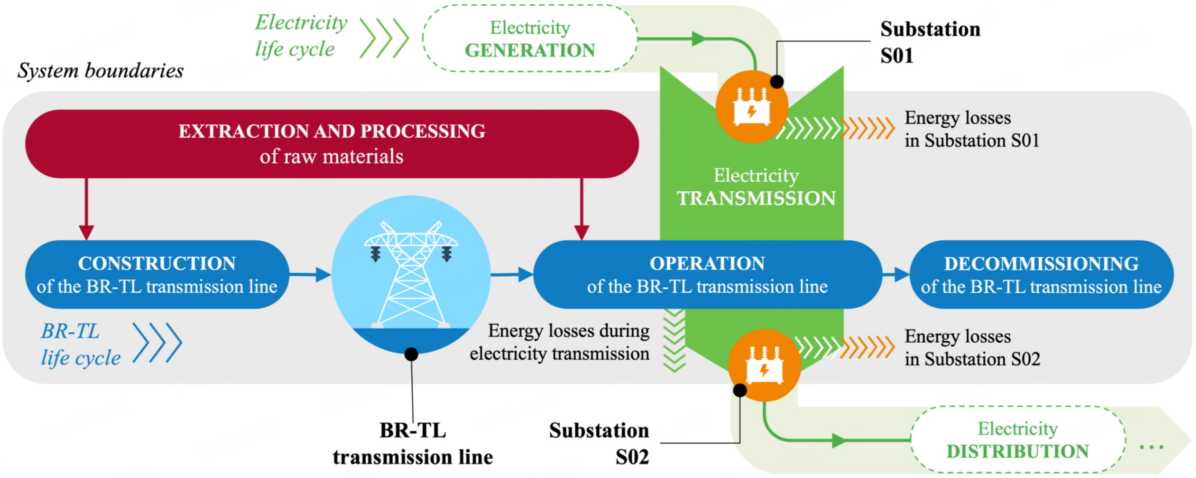

Figure 1. Scheme of the system boundaries considered in the carbon footprint analysis of transmitting electricity. Source: Elaborated by the authors.

initiative. Note that the Ecoinvent database is well-known and widely used in life cycle-based studies. The other tools are tailored to the Brazilian context, providing a better representation of its electricity sector and environmental aspects.

Electricity transmission scenario

Estimates of energy losses during electricity transmission and energy delivered by the BR-TL transmission line were performed through ANAREDE[22]. This analysis considered the static operating scenarios of the SIN developed by EPE, which is affiliated with the Brazilian Ministry of Mines and Energy, for 2024 to 2028. For the power flow calculations, the origin was established at the substation S01, while the destination was defined as the substation S02.

The static scenarios developed by EPE consider summer and winter periods and low, medium, and high load demands of the SIN, resulting in six scenarios each year. Since it was not possible to use operating scenarios from 1984 to 2024 - the period spanning from the start of the transmission line's operation to the year of the present research - this case study relied on the behavior of the electricity transmission system within these six scenarios from 2024 to 2028. Table 1 presents the average results for each EPE scenario within this timeframe, along with the corresponding energy losses observed during the operation of the BR-TL transmission line.

In this context, to accurately assess the energy losses associated with the entire life cycle of the BR-TL transmission line, we developed a variable scenario reflecting an average day that was extrapolated across the total number of operational days over the 40-year lifespan of the electricity transmission system. This average day was derived from the load profile of a typical week in which this system operates at high load for 15 hours, medium load for 94 hours, and low load for 59 hours. The summer scenario was applied to half of the year, while the winter scenario was assigned to the remaining half.

Table 2 provides a comprehensive overview of the total hours constituting the average day utilized for each static scenario, alongside the associated energy losses and the electricity delivered to substation S02. Based on the analysis, the energy loss percentage of 1.48% was adopted for the BR-TL transmission line, resulting in 29,754,685,286 kWh of electricity delivered to substation S02 throughout its 40 years of operation.

Table 1. Results of the average load flow transmitted and the average energy loss percentage for each static scenario considered for the operation of the SIN in the 2024-2028 period

Scenario (2024-2028)	Average power flow(MW)	Average energy loss(%)
Summer, high load	125.78	2.21 ± 0.04
Summer, medium load	125.18	2.18 ± 0.05
Summer, low load	45.78	0.79 ± 0.03
Winter, high load	83.93	1.47 ± 0.02
Winter, medium load	95.55	1.66 ± 0.02
Winter, low load	32.83	0.58 ± 0.06

SIN: Brazilian Interconnected System.

Table 2. Scenario of hours per load level created for an average day of the SIN operation, the respective energy losses in the BR-TL transmission line, average power flow, and the electricity delivered to substation S02

Load	Hours	Average energy loss Summer-Winter (%)	Average power flow Summer-Winter (MW)	Electricity delivered in S02 (kWh)
High	2.143	1.84	104.85	3,280,385,357
Medium	13.428	1.92	110.37	21,637,846,571
Low	8.428	0.68	39.30	4,836,453,357
Total	24.00	1.48	84.92	29,754,685,286

SIN: Brazilian Interconnected System; BR-TL: transmission line in Brazil.

Additionally, the electricity generation mix associated with the BR-TL transmission line was derived from an LCI defined by the Ecoinvent 3.8 database[23] for the Central-West region of Brazil, where this transmission line is situated. Table 3 details the composition of the electricity generation mix, which includes contributions from hydroelectric, thermal, and renewable sources, to provide further context for the study.

Life cycle inventory

Concerning the construction stage of the electricity transmission system analyzed, this case study focuses on land use change and the main material and energy inputs. This involves assessing the GHG emissions from vegetation suppression, as well as the upstream supply chain of building materials, including reinforced concrete, steel structures, metals, plastics, and insulating materials. It also addresses energy consumption from diesel oil and excavation activities.

The quantification of GHG emissions resulting from land use change is based on the estimated carbon content of the vegetation below and immediately next to the BR-TL transmission line that was cleared before its construction on behalf of its safe and efficient operation. This analysis assumes that the carbon stock in the biomass suppressed would be released entirely as CO_2. It also employs GHG emissions factors from the Emisfera Platform[24] and geoprocessing tools within the ArcGIS PRO software, in conjunction with land cover and use data from MapBiomas[26] for 1985, to determine the BR-TL transmission line corridor area.

On the one hand, MapBiomas is an initiative with an open platform that operates collaboratively with various institutions focused on different biomes and cross-cutting themes to generate annual land cover and use mapping, with data dating back to 1985[26]. On the other hand, the Emisfera Platform is a resource employed in the Brazilian electricity sector to create the GHG emissions inventory by utilizing information

Table 3. Description of the electricity generation mix associated with the BR-TL transmission line

Energy source	Baseline (%)
Hydro	40.04
Wind	-
Solar PV	-
Biomass	12.16
Natural gas (Combined cycle)	9.84
Natural gas (Conventional cycle)	6.03
Coal	0.46
Oil and other fossil fuels	3.79
Nuclear	4.22
Imported from the Northeast region of Brazil	5.58
Imported from the North region of Brazil	17.88

BR-TL: transmission line in Brazil; PV:photovoltaic.

from primary sources. It gathers location-specific data through direct communication with organizations and businesses[24].

Hence, the BR-TL transmission line was delineated by a 30-meter-wide corridor between the S01 and S02 substations, resulting in an area of 336.36 ha. Since the land cover and use data used in this study are from 1985, the year following the operational initiation of the BR-TL transmission line, the vegetation coverage within its corridor was estimated based on the land cover and use surrounding it. In this sense, a 60-meter buffer was established, corresponding to a 120-meter-wide corridor along the BR-TL transmission line. This broader corridor was selected to enhance sampling efficacy, given that the MapBiomas data are provided at a scale of 1:100,000[26]. Table 4 shows the land cover and use area for the 336.36 ha of the BR-TL transmission line corridor, highlighting the primary vegetation coverage and additional categories.

Owing to the absence of data from primary sources concerning other processes during the construction stage, their elementary flows were estimated by adapting LCIs from existing electricity transmission lines in the Ecoinvent 3.8 database[23]. First, we selected the data that best represented the quantities and specifications of the main equipment used in the transmission line and the S01 and S02 substations. Subsequently, we used the voltage levels of transmission lines and transformers at these substations as parameters for the LCI adaptations [Table 5 and Table 6]. For transportation throughout all life cycle stages, this case study incorporated transport activities that considered relevant suppliers within the region and country for the foreground processes. Conversely, for the background processes, it employed data from the Ecoinvent 3.8 database[23] for the LCIs used in the electricity transmission system being studied.

Regarding the operation stage, this case study considers transportation activities for facility maintenance and energy losses during electricity transmission (see the Electricity transmission scenario item). Transportation activities include using a helicopter for annual inspections, which would require four minutes of flight time per kilometer, and for ten-yearly inspections, which would take eight minutes of flight time per kilometer[3]. The outputs generated during the operating stage include nitrous oxide (N_2O) formation, resulting from air ionization surrounding the transmission line conductors in a high electric field[23] [Table 7].

Our analysis also encompasses the main material inputs of the S01 and S02 substations, such as lubricating oil and sulfur hexafluoride (SF_6) insulating gas, diesel oil consumption, and energy losses in the

Table 4. Land cover and use for the BR-TL transmission line corridor

Land cover and use	Area[26] (ha)	Carbon content[24] (tC/ha)	Suppressed carbon stock (tCO2eq.)
Lowland seasonal semideciduous forest	4.91	145.37	2,620
Forest savanna	229.43	103.45	87,026
Other categories	102.02	-	-
Total	336.36	-	89,644

BR-TL: transmission line in Brazil.

Table 5. LCI for the BR-TL transmission line construction stage

Inputs/Outputs	Unit	Amount	Source
Resources			Estimated based on MapBiomas[26] and Emisfera[24]
Land use	ha	336.36	
Material inputs			Adapted from Ecoinvent 3.8[23]
Wrought aluminum alloy	kg	356,727.89	
Gravel	kg	980,371.48	
Mastic asphalt	kg	441.60	
Concrete	m^3	19,724.73	
Copper cathode	kg	30,652.60	
Lead	kg	15,055.38	
Packaging film	kg	7.516,45	
PVC (emulsion polymerized)	kg	959.55	
PVC (suspension polymerized)	kg	960.92	
Ceramic	kg	35,164.92	
Wood	m^3	10.74	
Unalloyed steel	kg	868,446.75	
Low-alloyed steel	kg	38,945.25	
Energy inputs			Adapted from Ecoinvent 3.8[23]
Diesel	MJ	14,311,596.47	
Processes			
Excavation	m^3	89,706.91	
Emissions to air			
CO_2 fossil	kg	1,073,369.74	
Transport activities			Estimated
Transmission cables and towers	tkm	788,593.47	
Building materials	tkm	228,951.58	

LCI: life cycle inventory; BR-TL: transmission line in Brazil.

transformers. Note that the operational technical team from these electrical substations provided information on lubricating and diesel oil consumption. In contrast, information regarding SF_6 insulating gas was obtained from the Ecoinvent 3.8 database[23]. Furthermore, the operational technical team at the S01 substation reported energy losses in the transformers at a rate of 1%. In the absence of primary data for energy losses associated with substation S02, the same 1% energy loss rate was adopted for its transformers. Concerning the outputs of the operation stage of the S01 and S02 substations, this case study specifically addresses the management of lubricating oil waste, the fugitive emissions of SF_6, and CO_2 emissions associated with diesel fuel combustion [Table 8].

Table 6. LCI for the S01 and S02 substations construction stage following allocation procedures

Inputs/Outputs	Unit	Electrical substation		Source
		S01	S02	
Material inputs				Adapted from Ecoinvent 3.8[23]
Batteries	kg	381.36	352.02	
Emergency generators	kg	3,000.00	461.54	
Transformers	kg	44,931.00	39,024.92	
Capacitors	kg	–	13,846.15	
Circuit breakers	kg	1,601.25	492.69	
Insulators	kg	168.30	51.78	
SF_6	kg	0.81	0.81	
Energy inputs				
Diesel	MJ	555,840.00	171,027.69	
Transport activities				
Equipment distribution	tkm	87,644.75	88,394.77	
Emissions to air				
CO_2 fossil	kg	37,519.20	9,620.31	

LCI: life cycle inventory; SF_6: sulfur hexafluoride.

Table 7. LCI for the BR-TL transmission line operation stage

Inputs/Outputs	Unit	Amount	Source
Product			Estimated based on ANAREDE[22]
Electricity delivered	kWh	29,020,545,318.29	
Energy losses			Adapted from Ecoinvent 3.8[23]
Energy losses in transmission	kWh	439,973,183.81	
Emissions to air			
N_2O	kg	145,102.73	[3]
Transport activities			
Maintenance with helicopter	hour	359.53	

LCI: life cycle inventory; BR-TL: transmission line in Brazil; N_2O: nitrous oxide.

Table 8. LCI for the S01 and S02 substations operation stage following allocation procedures

Inputs/Outputs	Unit	Electrical substation		Source
		S01	S02	
Material inputs				Adapted from Ecoinvent 3.8[23]
SF_6	kg	696.49	214.31	
Lubricating oil	kg	2,376.00	365.54	Operational technical team (primary data source)
Diesel	MJ	500,256.00	128,270.77	
Energy losses				
Energy losses in transformers	kWh	300,541,972.96	293,136,821.40	
Emissions to air				Adapted from Ecoinvent 3.8[23]
SF_6	kg	696.49	214.31	
CO_2 fossil	kg	37,519.20	9,620.31	
Waste treatment				
Lubricating oil waste	kg	2,376.00	365.54	

LCI: life cycle inventory; SF_6: sulfur hexafluoride.

The decommissioning stage of the BR-TL transmission line and the S01 and S02 substations includes the end-of-life scenarios for their primary components and materials without considering the reuse of any equipment. On the one hand, an end-of-life recycling scenario was assumed for aluminum, electronic materials, copper, and reinforced concrete waste. On the other hand, the polyvinyl chloride (PVC) waste was designated for incineration. It is worth noting that the transportation activities of this stage correspond to the hypotheses adopted in the LCIs for treating these wastes available in the Ecoinvent 3.8 database[23].

RESULTS

Life cycle impact assessment

This section comprehensively analyzes the carbon footprint associated with electricity transmission through the BR-TL transmission line based on GHG emission factors from the Emisfera Platform[24] and the ReCiPe 2016 method[25]. The latter is a recent and widely used LCIA method whose global warming impact category is based on the Intergovernmental Panel on Climate Change (IPCC)[27]. It harmonizes modeling principles and choices, providing results at both midpoint and endpoint levels[25].

Over an estimated operational lifespan of 40 years, this electricity transmission generates 315,885.00 tCO_2 eq., corresponding to 10.89 gCO_2eq. per kWh delivered. During the construction stage, the carbon footprint was measured at 3.54 gCO_2eq./kWh. As for the operation stage, the electricity transmission through the BR-TL transmission line is linked with 7.34 gCO_2eq./kWh. In the decommissioning stage, an estimated 0.01 gCO_2eq./kWh is emitted. Table 9 provides a breakdown of these results by the life cycle stage of the transmission facilities, highlighting the main contributors.

DISCUSSION

Interpretation

Analysis of relevant issues

The life cycle of transmitting electricity through the BR-TL transmission line results in a carbon footprint of 10.89 gCO_2eq./kWh. The construction stage accounts for more than 32% of these GHG emissions (3.54 gCO_2eq./kWh) [as shown in Figure 2], primarily due to land use (87%) and building materials (approximately 11%), as detailed in Figure 3. These results become particularly significant since previous life cycle-based studies on electricity transmission[3,12,13,15] have overlooked land use change. Indeed, our findings emphasize the importance of addressing land use change as a critical environmental factor, potentially one of the main contributors to GHG emissions associated with electricity transmission. Note that this issue is especially pertinent in regions with extensive vegetation coverage, such as the Brazilian territory.

The operation stage is responsible for over 67% of the carbon footprint of transmitting electricity via the BR-TL transmission line (7.34 gCO_2eq./kWh) [refer to Figure 2]. The main sources of GHG emissions during this stage are the energy losses during electricity transmission and those associated with the S01 and S02 transformers. Another significant contributor is N_2O emissions from the corona effect - caused by air ionization around the transmission line conductors from the high electric field, as illustrated in Figure 4. Finally, the decommissioning stage contributes to less than 1% of total GHG emissions (0.01 gCO_2eq./kWh) in the life cycle of transmitting electricity via the BR-TL transmission line [also shown in Figure 2].

Based on these findings, we can explore strategies to minimize the carbon footprint of electricity transmission through the BR-TL transmission line. During the operation stage, our findings highlight the need to reduce GHG emissions associated with power losses in transmission lines. This is especially pertinent in regions where the electricity generation mix includes fossil fuels. In Brazil, energy losses can be managed through a systematic approach involving key stakeholders within the national electricity sector,

Table 9. Carbon footprint results from transmitting 1 kWh of electricity through the BR-TL transmission line

Transmission facilities/main contributors	GHG emissions(gCO_2eq./kWh)
Construction stage	3.54
BR-TL transmission line	3.49
Land use	3.09
Building materials	0.36
Others	0.05
Substation S01	0.01
Substation S02	0.03
Operation stage	7.34
BR-TL transmission line	3.63
Energy losses	2.14
N_2O emissions	1.49
Others	< 0.01
Substation S01	2.09
Energy losses	1.46
SF_6 emissions	0.63
Others	< 0.01
Substation S02	1.62
Energy losses	1.42
SF_6 emissions	0.19
Others	< 0.01
Decommissioning stage	0.01
BR-TL transmission line	0.01
Substation S01	< 0.01
Substation S02	< 0.01

BR-TL: transmission line in Brazil; N_2O: nitrous oxide; SF_6: sulfur hexafluoride.

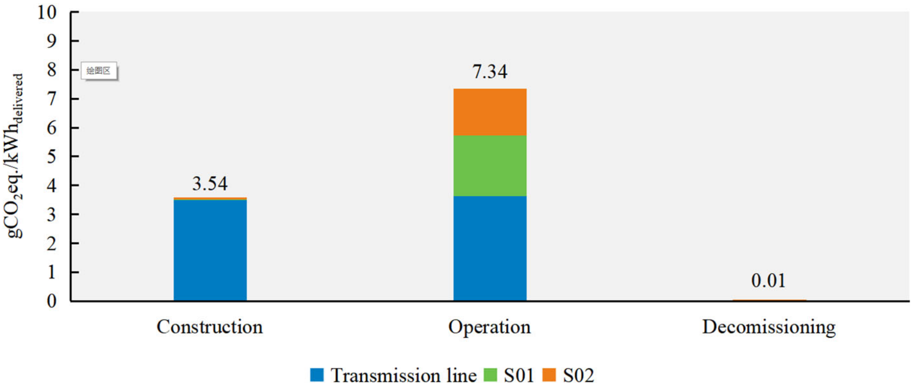

Figure 2. Life cycle stages' contribution to the carbon footprint of transmitting electricity through the BR-TL transmission line. Source: Elaborated by the authors. BR-TL: transmission line in Brazil.

such as the National Electric System Operator (ONS) and the Brazilian Electricity Regulatory Agency (ANEEL).

On the other hand, the company responsible for electricity transmission can address fugitive SF_6 emissions. Although these emissions account for only 3% of GHG emissions during this stage, they are significant due to the concentrated nature of this single gas leakage occurring in assets under the company's control

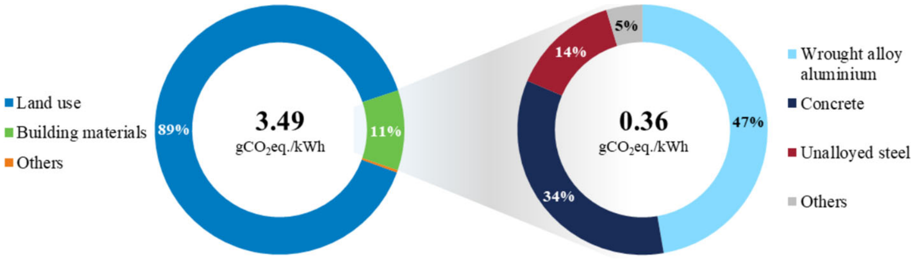

Figure 3. Main contributors to the carbon footprint of the transmission line construction stage.

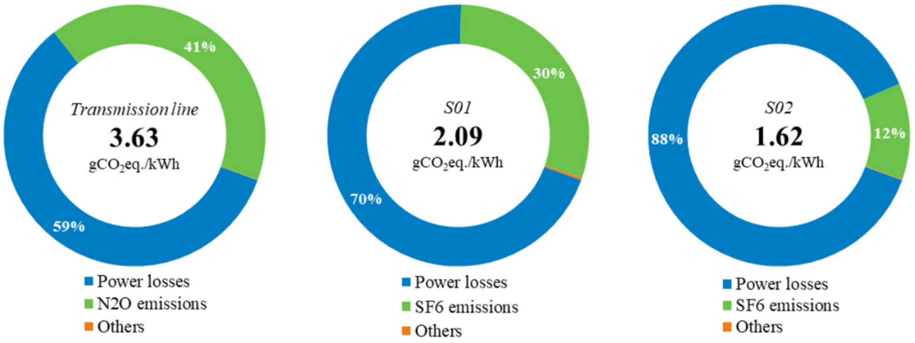

Figure 4. Main contributors to the carbon footprint of the operation stage of the transmission line and S01 and S02 substations.

management. Note that mitigation strategies related to the operation stage can be employed not only for new projects but also for existing electricity transmission lines, enabling improvements to the current infrastructure. In the construction stage, GHG emissions resulting from vegetation suppression related to land use change can be mitigated by selecting alternative corridors for transmission lines and optimizing corridor dimensions through the efficient design and shared use of transmission infrastructure. This strategy is particularly relevant for future electricity transmission lines, ensuring that new projects contribute to reducing the energy sector's carbon footprint.

By identifying the main contributors to transmission-related emissions and exploring strategies to mitigate them, this paper offers valuable insights for policymakers, utility companies, and stakeholders focused on enhancing the sustainability of energy infrastructure not only in Brazil but also worldwide. Ultimately, as Brazil increasingly adopts renewable energy sources and expands its EV fleet, these insights can help optimize the integration of energy transition and electrification in transportation, fostering a more sustainable and resilient electricity system in the country.

Sensitivity analysis

This case study includes two sensitivity analyses. The first analysis assesses the impact on the carbon footprint of transmitting electricity through the BR-TL transmission line, considering two scenarios for the Brazilian electricity mix. One scenario corresponds to the electricity mix associated with the lowest GHG emissions observed in the country, while the other represents the most carbon-intensive electricity mix. The second sensitivity analysis involves assessing a scenario where the entire corridor of the BR-TL transmission line would be covered by vegetation whose carbon content is equivalent to the average carbon content between lowland seasonal semideciduous forest and forest-savanna (see the Life Cycle Inventory item) before the transmission line construction.

The first sensitivity analysis was developed considering the influence of the electricity mix associated with the electricity transmission system in accounting for GHG emissions, mainly due to energy losses. Following the Brazilian Ministry of Science, Technology, and Innovation publications[28,29] on the CO_2 emission factors of electricity generation in the SIN, the scenarios with the lowest and highest GHG emissions for the Brazilian electricity mix were observed in May 2007 and September 2021, respectively. Table 10 provides estimates of the carbon footprint for these two scenarios compared with the Baseline (electricity mix of the Central-West region of Brazil).

As a result, the carbon footprint of electricity transmission through the BR-LT transmission line is directly linked to the GHG emissions related to the electricity mix. When the GHG emissions are lower (lowest GHG emission scenario), the potential global warming impacts from transmitting electricity through the BR-LT transmission line (9.14 gCO_2eq./kWh) are approximately 16% lower than the results obtained by the Baseline (electricity mix of the Central-West region of Brazil) (10.89 gCO_2eq./kWh). On the other hand, when GHG emissions associated with the electricity mix are higher (highest GHG emission scenario), these impacts (13.06 gCO_2eq./kWh) are approximately 20% higher than those of the Baseline (10.89 gCO_2eq./kWh) [see Figure 5].

In the second sensitivity analysis, we considered an emission of 153,437 tCO_2eq. associated with vegetation suppression due to the corridor of the BR-TL transmission line. This represents a more than 70% increase compared to the GHG emissions of 89,644 tCO_2eq. obtained in the Baseline. This implies a 20% increase in the carbon footprint of transmitting electricity through the BR-TL transmission line, which rose from 10.89 gCO_2eq./kWh to 13.08 gCO_2eq./kWh [refer to Figure 5]. This indicates that vegetation suppression associated with constructing a transmission line can significantly impact the carbon footprint of its electricity transmission.

Limitations

The present study is subject to limitations arising from dependence on secondary data sources throughout the complete life cycle of electricity transmission via the BR-TL transmission line. Although we explored available primary data in collaboration with the BR-TL transmission line's technical team and other relevant stakeholders, we encountered significant challenges in accessing all the necessary technical information regarding the construction and operation of this system's transmission line, including the S01 and S02 substations. This mainly impacted evaluating certain building materials and equipment, energy inputs, transport activities, allocation procedures, energy losses of the S02 transformers, maintenance, fugitive emissions and the replacement of SF_6, and end-of-life scenarios for waste from the BR-TL transmission line. In these cases, our analysis relied on secondary data. Given that this reliance may introduce uncertainties, we have taken steps to address them by incorporating sensitivity analyses and transparently discussing the assumptions and potential variability in our results.

Additionally, this study does not explore the potential of advanced equipment and innovative technologies[30] to reduce energy losses and fugitive emissions in electricity transmission systems. Another limitation is adopting a scenario for electricity transmission over the 40-year useful life of the BR-TL transmission line based on static operating scenarios of the SIN prepared by EPE for 2024-2028. While this was the most suitable option for the present case study, improvements could be made by obtaining data compatible with the study's time horizon or historical operation data of the analyzed electricity transmission system.

Table 10. Description of the Brazilian electricity mix's lowest and highest GHG emissions scenarios

Energy source	Baseline (%)	Lowest GHG emission scenario		Highest GHG emission scenario	
		(TWh)	(%)	(TWh)	(%)
Hydro	40.04	35.07	95.10	26.71	53.00
Wind	–	0.04	0.10	7.36	14.60
Solar PV	–	–	–	0.81	1.60
Biomass	12.16	–	–	2.27	4.50
Natural gas	15.87	0.37	1.00	7.46	14.80
Coal	0.46	0.30	0.80	1.71	3.40
Oil and other fossil fuels	3.79	0.04	0.10	2.67	5.30
Nuclear	4.22	1.07	2.90	1.41	2.80
Others	23.46	–	–	–	–
Total	100.00	36.88	100.00	50.39	100.00

GHG: greenhouse gas; PV: photovoltaic.

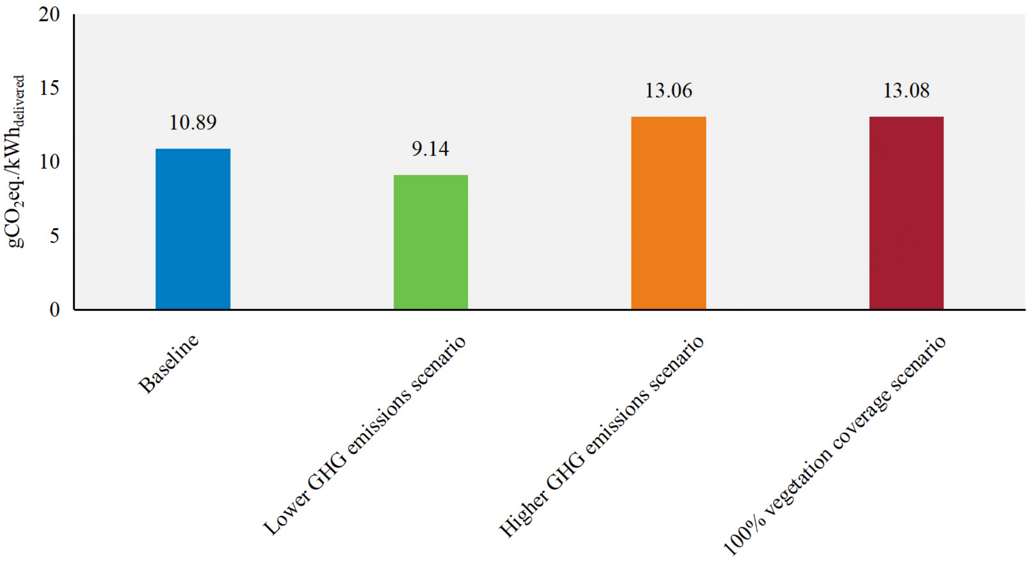

Figure 5. Carbon footprint comparison between the scenarios defined for the Brazilian electricity mix and the vegetation coverage. Source: elaborated by the authors.

Despite these limitations, the study's methodology and findings remain robust due to the use of reputable and validated secondary sources and conservative assumptions where necessary. These measures ensure that the results provide meaningful insights into the carbon footprint of electricity transmission via the BR-TL transmission line while acknowledging the scope for refinement through future research.

CONCLUSIONS

This paper addressed the carbon footprint of electricity transmission by quantifying the GHG emissions at various stages of transmitting electricity through a case study in Brazil. For this purpose, our analysis focused on an electricity transmission system composed of the BR-TL transmission line and the S01 and S02 substations. In this context, a comprehensive electricity transmission scenario was developed for this system utilizing the ANAREDE software. Our analysis also incorporated detailed data on land use and relevant inputs and outputs related to the construction, operation, and decommissioning stages throughout the life cycle of the electricity transmission system.

The carbon footprint analysis revealed that transmitting electricity through the BR-TL transmission line results in 10.89 $gCO_2eq.$ per kWh delivered. Our findings indicated that the operation stage is responsible for over 67% of these GHG emissions, predominantly due to energy losses during electricity transmission and those associated with the S01 and S02 transformers. They also highlighted the relevance of the construction stage, contributing more than 32% of the carbon footprint, which is mainly linked to GHG emissions resulting from land use change.

The sensitivity analyses conducted in this study provided valuable insights into the factors that significantly influence the carbon footprint of electricity transmission. By examining two scenarios for the Brazilian electricity mix, we found that the carbon footprint of transmitting electricity via the BR-TL transmission line is highly sensitive to the electricity generation mix's GHG emissions profile. In a low-emission scenario, the carbon footprint decreased by 16%, while in a high-emission scenario, it increased by 20% compared to the Baseline. This finding highlights the importance of decarbonizing electricity generation to minimize the environmental impact of electricity T&D grids. Additionally, the sensitivity analysis of land use change demonstrated its significant effect on the carbon footprint. In a scenario where the corridor of the BR-TL transmission line would originally be covered solely by dense vegetation, the carbon footprint of its electricity transmission rose by 20% compared to the Baseline, driven by a 70% rise in GHG emissions due to land use change. This underscores the critical need to consider land use change in environmental assessments of electricity transmission projects, especially in regions with extensive forest coverage, such as Brazil.

Finally, this paper offered valuable insights for sustainable electricity transmission infrastructure development, aligning with national climate targets and supporting global decarbonization efforts. Future studies could focus on gathering more detailed primary data from the BR-TL transmission line and the S01 and S02 substations. These data should include information about building materials, equipment, maintenance activities, and energy losses in substations. Additionally, exploring more advanced equipment and innovative technologies - particularly those related to energy losses and fugitive emissions in electrical substations - would be highly beneficial. These efforts would lead to a more accurate understanding of the carbon footprint associated with electricity transmission.

Adopting a more dynamic modeling approach that encompasses the entire 40-year lifespan of the BR-TL transmission line is also recommended. This modeling could incorporate projections for changes in the electricity mix, technological advancements, and shifts in energy demand patterns. Furthermore, expanding the analysis to consider the impact of EV adoption on electricity T&D grids in Brazil, as well as addressing other environmental concerns such as water footprint and land use, would provide a more comprehensive and updated understanding of the sustainability of electricity transmission systems in the country.

DECLARATIONS

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Software, writing - original draft preparation, and visualization: Lassio, J. G.
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Availability of data and materials

The data presented in this work are available from the corresponding author upon reasonable request.

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All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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