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A Proposal to Reduce Greenhouse Gas Emission in the Electrical Power Transmission Sector in Brazil: A Calculation Method Based on the Use of Natural Ester in Power Transformers

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SUMMARY

Looking to propose a potential reduction of Carbon Dioxide (CO_2) emissions in the electrical power transmission sector in Brazil, this article presents a hypothetical study considering the use of natural ester as insulating liquid in the total number of power transformers (also including autotransformers and shunt reactors) foreseen in the government program for the expansion of electricity transmission. CO_2 is the main Greenhouse Gas (GHG), and a possibility of reducing its emission could be achieved by the exchange of the petroleum-based insulating liquid for an environmentally friendly insulating liquid like natural ester. This proposal could help with Brazilian strategy to mitigate GHG emissions in the electrical power sector and thus could contribute to the fulfilment of the Brazilian determined contribution assumed in the scope of the Paris Agreement. Most of the insulating liquids used in electrical power transmission transformers in Brazil is petroleum-based (mineral oils). But, in the last two decades, due to the low biodegradability of mineral oil and its low fire point, the use of environmentally friendly (biodegradable and non-toxic) and safer (with a higher fire point) alternative insulating liquids has increased globally including high-voltage large power transformers. The 2020 data base of the transmission expansion program in Brazil contains all the recommended expansion works for the interconnected system (that have not yet been authorized or auctioned) planned for 2021-2033 period. The investment associated only with works in electrical substations (new or expansion / reinforcement) total amounts approximately R$ 17 billion. In the description of each electrical substation work, are presented details of the planned equipment, such as number of units, voltages, number of phases and power rating. The article presents a summary of the 590 new power transformers officially planned to be incorporated into the Brazilian interconnected system, estimates the volume of insulating liquid used in these equipment, and using the technical information on the differences in CO_2 emission for mineral oil and natural ester over their complete life cycle, the article applies a calculation method to quantify and proposes the potential reduction of GHG emission considering a hypothetical condition (and not a Brazilian government policy) that all the 590 new power transformers could be specified with natural ester. This paper also describes references of high voltage power transformers with natural ester in operation in Brazil and part of the interconnected system. It's known that a major environmental impact on transformers comes from their losses, but this article proposes a specific cut when analysing the GHG emissions of one of the main transformer's component: the insulating liquid. The article concludes evaluating the benefits of using natural ester over mineral oil mainly considering the GHG emissions "from the cradle to the grave" of these two products. The proposal of natural ester in power transformers in the electrical power transmission sector could allow a reduction of GHG emissions in Brazil, presenting a potential contribution to fulfill the goals established by Brazil for the Paris Agreement.

KEYWORDS

GHG, Power Transformers, Insulating Liquid, Natural Ester, Transmission, Grid Expansion, CO_2 Emissions, Paris Agreement.

1 - INTRODUCTION

Between 2019 and 2030, Brazil will have a growth in electricity demand around 40%, reaching 762 TWh. To meet this demand, it will be necessary to add more than 37,000 km of new transmission lines. In this context, the expansion of electrical power transmission grid in Brazil brings major challenges related to energy efficiency and the reduction of greenhouse gas emissions in the sector.

Transformers (as well as autotransformers and shunt-reactors) are important equipment when it comes to energy efficiency in the transmission and distribution of electricity, considering that it is estimated that 30% of technical losses come from this equipment. In terms of greenhouse gas emissions in the Brazilian electricity sector, it is known that most of them come exclusively from generation, especially when using fossil fuel thermal power plants.

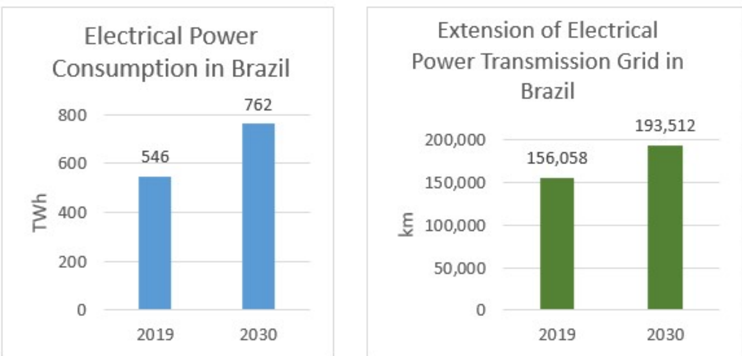
It is in this context that this paper proposes a method for calculating the potential reduction of greenhouse gas emissions, considering, hypothetically (and not a Brazilian government policy), that all transformers officially planned for the expansion of electrical power transmission grid in Brazil could be filled with insulating liquid type natural ester of renewable source. This paper also presents references of high voltage power transformers with natural ester in operation in Brazil and part of the transmission interconnected system.

The conclusions show that the proposal to potentially reduce greenhouse gas emissions in the power transformers for the expansion of electrical power transmission grid in Brazil, until 2030, could contribute to the Brazilian commitment signed under the Paris Agreement to mitigate its emissions.

2 - THE EXPANSION OF ELECTRICAL POWER TRANSMISSION IN BRAZIL

To understand the expansion of electrical power transmission in Brazil, it is essential to use the 2030 Ten-Year Energy Expansion Plan - PDE 2030 [1] as a reference. The PDE is a report annually prepared by the Energy Research Company (EPE), under the guidelines of the Ministry of Mines and Energy (MME) of Brazil, which indicates the prospects for expansion of the energy sector in a ten-year horizon (in this case, 2021-2030) within an integrated vision for the several energy sources.

In the PDE 2030 reference scenario, total electricity consumption in Brazil will increase from 546 TWh in 2019 to 762 TWh in 2030, representing a growth of 39.6%, as shown in Figure 1a. To meet this increase in demand, specifically in electrical power transmission grid, there is a forecast to add 37,454 km of new transmission lines by the year 2030, representing a 24% increase in the total extension of the Brazilian system, as shown in Figure 1b (important to understand how many substations, transformers, autotransformers and shunt-reactors will be necessary). The foreseen investment for the expansion in substations alone is R$ 27.1 billion (~US$ 4.9 billion).



(a) (b)

Figure 1 – (a) Growth in electrical power consumption in Brazil between 2019-2030. (b) Expansion of the electrical power transmission grid in Brazil between 2019-2030 – Source: Prepared by the author with data from PDE 2030 [1].

It is observed that part of the expansion in Brazil will be with large interconnections systems that will increase the capacity for electrical exchange between subsystems and transmission lines aiming to drain the power generation of the Belo Monte Hydro Power Plant (HPP) in the North of the country, wind farms in the Northeast and photovoltaic and thermal plants in the Southeast. The expansion of the electrical power transmission grid is also taking place to meet the increased demand for electricity, especially in the large cities in the country.

2.1 - Efficiency in the power transformers of Brazilian electrical power transmission grid

An important point in the PDE 2030, is the consideration of energy efficiency. Energy efficiency is a relevant resource for the medium and long-term energy planning for any country, as it is one of the most economical ways to increase the security of energy supply. The PDE 2030 states that the improvement of electrical efficiency in Brazil can contribute with 32 TWh in 2030, which will correspond to the power generation of a HPP with an installed capacity of around 7 GW, equivalent to the Brazilian part of the Itaipu HPP.

As an alternative to increase the supply of the system without, necessarily, a physical expansion, it is essential to evaluate the possibility of reducing technical losses in electrical power transmission and the use of more efficient technologies. In the electrical power transmission system, the reduction of losses in transformers is relevant for the energy conservation programs, because, according to Campos [2], data released by the Brazilian Energy Conservation Program (PROCEL) showed that of all the electricity generated in Brazil in 2005, 14% was wasted by global losses in transmission and distribution, and 30% of these technical losses were concentrated in transformer cores.

The transformers energy efficiency has huge potential to, in addition to boosting economic growth, also avoid the emission of Greenhouse Gases (GHG) from power generation. The relevance of the topic is evidenced by the publication of the standard IEC 60076-20 [3] supported by ambitious climate policies imposed by the European Union, as well as the process of publication in Brazil of the standard ABNT NBR 5356-20 - Power Transformers - Energy Efficiency, led by the power transformers committee of the Brazilian Committee for Electricity, Electronics, Lighting and Telecommunications (COBEI).

These standards of efficiency promote a higher average level of energy performance for transformers due to the need to save energy and reduce GHG emissions, proposing methods for specifying transformers with higher energy performance according to the applicable load and operating conditions, seeking more economical solutions throughout the entire life cycle of transformers.

2.2 - Greenhouse gas emissions in the Brazilian electricity sector

The reason that motivates the development of this paper is to propose the reduction of GHG emissions in electrical power transmission transformers in the Brazilian Electricity Sector (SEB) through the use of natural ester insulating liquid from renewable source, carbon neutral, even recognizing that the great environmental impact in transformers comes from their losses.

For a more complete and broader analysis of the expansion of Brazilian electrical power transmission grid, it is also important to assess GHG emissions in details in this sector. According to the report by the Intergovernmental Panel on Climate Change (IPCC) [4], Carbon Dioxide (CO_2) is a naturally occurring gas and also a by-product of burning fossil fuels, deforestation and industrial processes. CO_2 is the main GHG, being a reference for calculating emissions.

According to Brazilian Energy Balance - BEN 2020 [5], in 2019, the total CO_2 emissions associated with the Brazilian energy matrix was 412 million tons of CO_2 equivalent ($MtCO_2eq$), where 46% of these emissions, came from the transport sector (191 $MtCO_2eq$). The electricity sector was responsible for 13% of these emissions with 56 $MtCO_2eq$. Most of these SEB emissions come exclusively from generation that, depending on hydrological conditions, under unfavorable conditions may be a need to switch-on fossil fuel thermal power plants.

The PDE 2030 projection shows that the total CO_2 emissions associated with the Brazilian energy matrix will be 484 $MtCO_2eq$ in 2030, with a growth of 17.5% compared to 2019. The electricity sector will be responsible for 41 $MtCO_2eq$, with a reduction of 26.8% compared to 2019, representing only 8.5% of total emissions in 2030, as shown in Figure 2. This projected reduction in GHG emissions in the electricity sector comes from the increase in the supply of generation from renewable sources such as wind, solar and biomass.

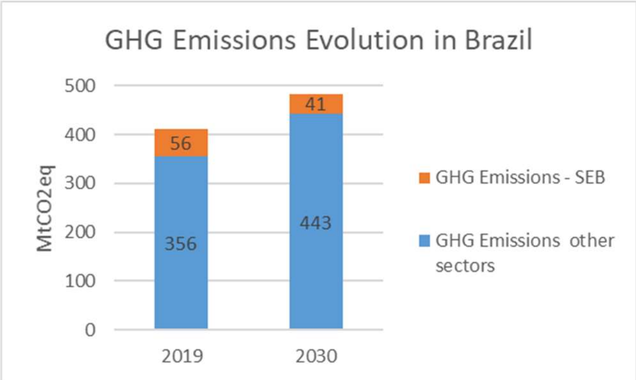


Figure 2 - Greenhouse gas emissions growth in Brazil between 2019-2030 – Source: Prepared by the author with data from BEN 2020 [5] and PDE 2030 [1].

2.2.1 - Brazilian Position on GHG emissions

Brazil, as a signatory to the Paris Agreement, assumed an important commitment to reduce GHG emissions. In its Nationally Determined Contribution (NDC) [6], Brazil has committed to reduce its emissions by 37% in 2025 and by 43% in 2030, based on 2005 emissions. The Brazilian NDC does not propose formal distribution of targets for each sector, but the energy sector foresees and adopts important measures and initiatives aimed at reducing emissions, mainly in energy production/generation.

Specifically in the SEB, indicators such as the participation of renewable sources in the generation matrix and energy efficiency gains, will have a relevant contribution to the Brazilian commitment. The existence of growth potential in the production of electricity from renewable sources should be used as a strategy to mitigate GHG emissions in the sector.

More recently, in 2018, a national Decree No. 9,578/2018 [7] brought the concept that GHG mitigation can be achieved through technological replacements that reduce the use of resources and emissions. It also presented emission limit projections by sector for the year 2020, where the energy sector had stipulated a limit of 868 $MtCO_2eq$. Actual emissions in 2020 are expected to be below this limit due to the economic downturn caused by the Covid-19 pandemic.

In this context, the expansion of electrical power transmission grid must be strategically aligned with the NDC's commitments, in order to also contribute to the reduction of GHG emissions. Once again, it is clear that the proposal of this paper on the use of a carbon neutral insulating liquid from renewable source (a technological replacement), can contribute to mitigate emissions in the most expensive equipment in the composition of an electrical substation: the power transformer.

2.3 - Transmission expansion program and long-term expansion plan

To understand how many transformers, autotransformers and shunt-reactors will be needed in Brazil to meet the electricity demand of 762 TWh and the consequent expansion of 37,454 km of new transmission lines by the year 2030, this paper uses the report Transmission Expansion Program (PET) / Long-Term Expansion Plan (PELP), which is a semiannual management report prepared by EPE, that contains all the National Interconnected System (SIN) expansion works recommended in the planning studies coordinated by EPE and which have not yet been authorized or bid for.

The PET/PELP report considered in this paper is the version issued in the 2020 Cycle 2nd Semester [8] that presents the details of works with expected dates of operation between 2024 and 2033. The PET details the works until the 2026 and the PELP details the works after 2027. The PET/PELP does not cover works that have already been authorized and that have already been tendered, but it has details of the date of needs for operation of constructions and investments planned for each piece of equipment and stage of the works.

3 - METHOD OF CALCULATION OF GHG EMISSIONS FOR NATURAL ESTER FILLED POWER TRANSFORMERS

As a basis for quantifying how much equipment is needed to expand the electrical power transmission grid in Brazil and to calculate GHG emissions considering natural ester filled power transformer, this paper uses the PET/PELP 2nd Semester 2020 but makes a cut by not considering 800 kVDC converter transformers. This paper also adopts a unique premise of calculating insulating liquid volume per MVA based on the author's experience.

Natural ester insulating liquid was selected by this paper for the method of calculating GHG emissions for power transformers because, as described by Da Silva [9], the increase in its use as an insulating liquid in transformers, instead to mineral oil, it is the result of advantages such as safety (it has a high fire point at approximately 360°C), environmental characteristics (biodegradable and non-toxic) and the life span extension of windings insulating paper (causes less degradation of the paper).

The Table 1 presents a summary of the 590 items planned in the PET/PELP 2nd Semester 2020, with information treated by the author, sorting by type (shunt-reactor, autotransformer or transformer), kV at high voltage (69, 138, 230, 330, 440, 500 and 525) and number of units. With a more technically focused look, it is possible to identify the profile of all equipment. In power rating, the 72 shunt-reactors add up to 3,573 MVAr, the 179 power transformers add up to 19,064 MVA and the 339 autotransformers add up to 52,666 MVA. From the 590 items planned, 363 (61.5%) are planned to be operational between 2024-2028 and 227 (38.5%) are planned to be operational between 2029-2033. Evaluating the size of the equipment from the perspective of voltage and power rating, 207 items (35.1%) have a high voltage ≥ 500 kV, while 143 items (24.2%) have a power rating ≥ 200 MVA.

Table 1 – Sorting of equipment planned for PET/PELP 2nd Semester 2020 - Source: Prepared by the author with data from PET/PELP [8].

Item	High Voltage (kV)	Number of Units	Subtotal
Shunt-Reactor	230	2	72
	500	37	
	525	33	
Autotransformer	230	184	339
	345	18	
	440	3	
	500	89	
	525	45	
Power Transformer	69	1	179
	138	2	
	230	127	
	345	33	
	440	13	
	500	3	
		590	

Based on the author's experience, an estimation of insulating liquid volume, in liters per MVA (l/MVA), for each type of equipment (shunt-reactor, autotransformer and power transformer), was done considering the number of phases (single-phase or three-phase), power rating (MVA or MVAr) and high voltage (69, 138, 230, 330, 440, 500 and 525 kV). The total volume calculated is approximately 18.3 million liters of insulating liquid for the 590 items planned for 2024-2033, with 1,066,000 liters for the shunt-reactors, 12,635,400 liters for the autotransformers and 4,570,000 liters for the power transformers.

To support the calculation of insulating liquid CO_2 emissions from the equipment, this paper uses as a reference the Building for Environmental and Economic Sustainability (BEES), which is a tool developed by the National Institute of Standards and Technology (NIST), a physical science laboratory part of the U.S Department of Commerce, to allow the selection of environmentally preferable and cost-effective products. According to Lippiatt [10], BEES measures the environmental performance of products using the environmental lifecycle assessment approach specified in the standard ISO 14040. All stages of a product's life are analyzed, such as raw material acquisition, manufacture, transport, installation, use and waste management.

The part of BEES that is specifically of interest to this paper, is the result of measuring the environmental performance of 4 different insulating liquids: one mineral, one silicone and two natural esters. More specifically, the cut of this paper is made to analyze and compare CO_2 emissions for naphthenic-based mineral oil and a particular natural ester made based on soybean oil (FR3™). CO_2 emissions are evaluated for each macro stage of the two products' life cycle. Values are given in kg/unit, where "unit" means a 1,000 kVA transformer filled with 500 gallons of insulating liquid during 30 years of operation.

Table 2 presents the carbon dioxide emissions (in gCO_2 equivalent / unit) for each macro stage of the life cycle for the 2 different types of insulating liquids selected. The highlight here is the performance of natural ester in the raw material stage, which has a negative value due to the absorption of CO_2 during the photosynthesis of soybeans crops.

Table 2 – Carbon dioxide emissions for 2 different types of insulating liquids – Source: Adapted by the author with data from Lippiatt [10].

	gCO_2eq / unit	
Stage	**Mineral Oil**	**Natural Ester**
Raw Material	1,048,184	-381,590
Manufacture	544,363	160,212
Transport	122,478	71,498
Use	154,124	153,450
Waste Management	30,825	30,690
Total	1,899,973	34,260

The total assessment of the CO_2 emissions for the 2 different types of insulating liquids shows that the natural ester oil has only 1.8% of the CO_2 emissions of mineral oil. Considering that the reference analysis is done considering 500 gallons of insulating liquid per "unit" and that each US gallon has 3.78 liters, it was calculated that 1 liter of mineral oil emits 1.005 $kgCO_2eq$, while 1 liter of natural ester emits 0.018 $kgCO_2eq$. Therefore, as the analysis proposed by this paper (not a Brazilian government policy), if hypothetically consider that all 590 equipment needed for the expansion of Brazilian electrical power transmission grid could use natural ester, it will be possible to stop emitting 18,039 tons of CO_2 equivalent (tCO_2eq), as shown in Table 3.

Table 3 – CO_2 emissions from insulating liquids – Source: Prepared by the author based on data from Lippiatt [10].

	Mineral Oil	**Natural Ester**
Emission of $kgCO_2eq$ per liter	1.005	0.018
Total volume of insulating liquid in liters	18,271,400	
Total emissions in tCO_2eq	18,368	329

4 – HIGH VOLTAGE NATURAL ESTER IMMERSED POWER TRANSFORMERS IN SERVICE IN BRAZIL

The use of natural ester insulating liquid in transformers has a strong appeal for application in renewable energies. According to BEN 2020, the installed capacity of electric power generation in Brazil from renewable sources, represented 84.6% in 2019, while the PDE 2030 estimates that the installed capacity of electric power generation will be 86% from renewable sources in 2030. Therefore, even with a 39.6% growth in total electricity consumption in the 2019-2030 period, Brazil will still maintain a high participation of renewable sources in the electric power generation matrix.

A case of high voltage natural ester immersed power transformers in service in Brazil with application in renewable energies, are the largest natural ester filled generator step-up transformers (GSU) in Latin America described by Da Silva [9]. Two three-phase natural ester immersed GSU transformers 200 MVA, 34.5/230 kV manufactured in Brazil, as showed in the Figure 3, connect a wind farm to the SIN. Another case, as described by Arantes [11], is one of the largest electrical power generation and power transmission companies in Brazil, that has more than 20 natural ester filled power transformers and shunt-reactors between 69 and 245 kV. Some of these equipment is in operation for more than 13 years without problems, as the case detailed by Da Silva [12].

Figure 3 – 200 MVA, 34.5/230 kV natural ester filled GSU transformer – Source: elaborated by the author

5 - CONCLUSIONS

Brazil, like most developing countries, faces the dilemma of expanding its energy infrastructure to meet growing demand while complying with international agreements and climate policies for low GHG emissions. The search for innovative technologies and the selection of environmentally friendly products is a way to reduce the negative environmental impacts associated with the energy sector, especially in electric power generation. More specifically in the electrical power transmission, the benefits of using natural ester over mineral oil could allow for more sustainable power transformers and substations, as it could mitigates GHG emissions.

The potential contribution to reducing GHG emissions by the insulating liquid of power transformers seems irrelevant when compared to the contribution to reduce total emissions from electric power generation (especially when using fossil fuels) or the contribution to reduce the transformer's losses. But the hypothesis proposed by this paper (and which is not a Brazilian government policy) with a potential use of natural ester insulating liquid for all the 590 equipment needed to expand electrical power transmission, by 2030, it makes possible for Brazil avoid emitting more than 18 thousand tons of equivalent CO_2. Thus could contribute to the Brazilian commitment signed under the Paris Agreement to mitigate its total emissions.

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