Supporting the development of Medium-Voltage Switchgear with Life Cycle Assessment and Circular Analysis: A Comparative Study of SF_6 and Synthetic Air Technologies

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Gases for electrical insulation are essential for the operation of electric power equipment, offering several advantages over liquid and solid insulation, including lower weight and cost, simpler manufacturing processes, recovery of insulation performance after partial discharge, and suitability for insulating moving parts (Rabie & Franck, 2018). Among these gases, SF_6 (sulphur hexafluoride) has become the preferred option for medium-voltage equipment, particularly in gas-insulated switchgear, due to its superior dielectric strength and rapid dielectric recovery characteristics (Kotharu & Sutherland, 2025; Li et al., 2018).

However, the growing concern over the environmental impact of SF_6 has led to increased regulatory pressure at the European level. Regulation (EU) 2024/573 on fluorinated greenhouse gases, which amends Directive (EU) 2019/1937 and repeals Regulation (EU) No 517/2014, establishes stricter measures to reduce the use of fluorinated gases, including SF_6, across various sectors. Given that 1 kg of SF_6 has an equivalent climate impact (global warming potential) to 24300 kg of CO_2 (Regulation (EU) 2024/573 of the European Parliament and of the Council of 7 February 2024 on Fluorinated Greenhouse Gases, Amending Directive (EU) 2019/1937 and Repealing Regulation (EU) No 517/2014 (Text with EEA Relevance), 2024), this regulation reinforces the urgency of developing and adopting SF_6-free alternatives in electrical equipment, such as medium-voltage switchgears.

In this context, a comprehensive evaluation of new designs becomes imperative, and Life Cycle Assessment (LCA) emerges as a relevant methodology to analyse and compare the environmental performance of this type of product. Due to the growing need for sustainable solutions, LCA provides an adequate framework for assessing these impacts, identifying key environmental hotspots, and supporting informed decision-making throughout the product's life cycle, ultimately guiding future developments towards more sustainable alternatives. The combination of LCA and Circular Economy (CE) creates a powerful synergy between circular innovation and systematic methods for assessing environmental, economic, and social impacts (Emilia Ingemarsdotter & Marina Dumont, 2022). As complementary and fundamental approaches, LCA and CE together provide a solid foundation for reducing waste and contamination while fostering innovation and economic efficiency, and LCA can be adapted to give valuable insight into the impact of CE strategies (Brändström & Saidani, 2022; Pereira, 2024).

The present study is part of the ATE project (*ATE – Aliança para a Transição Energética*, n.d.), which aims to promote the energy transition by 2030. The focus of this project is the reduction of greenhouse gas emissions (GHG) and decarbonization, aligned with the Roadmap for Carbon Neutrality 2050 (RNC2050), by improving material efficiency, integration of renewable energies and energy efficiency and promoting environmental sustainability and circular economy. In the case of secondary distribution, versatile and reliable solutions exist for the efficient control of medium-voltage networks. Switchgear is an essential component of this distribution network, playing a vital role in controlling, safeguarding, and isolating electrical equipment (*EFACEC Swithgear FLUOFIX 24 kV [2IS(M)+CIS] – EPD Italy*, n.d.). Given their material composition and long service life, assessing the environmental impacts of switchgear is particularly interesting.

In this work, two case studies were considered, based on data provided by EFACEC for medium-voltage switchgears. The first focuses on switchgear Fluofix 24 kV (with SF_6), serving as the reference product for material use, environmental performance, and circularity metrics. The second examines switchgear evoFIX (without SF_6, with synthetic air), highlighting alternative technologies and their potential advantages. To assess the environmental implications of developing an SF6-free alternative, a LCA was first conducted for both products to establish a baseline, compare their environmental impacts, and identify key hotspots. As expected for this type of product, the main environmental hotspot is electricity consumption during the use phase, followed by the materials used in manufacturing, particularly metals such as copper, steel, stainless steel, and aluminium. Following this, and to support future decision-making, a set of circularity indicators was selected and applied based on the ISO 59020 framework (*ISO 59020:2024(En), Circular Economy — Measuring and Assessing Circularity Performance*, n.d.). The mandatory indicators defined in Annex A were considered the core basis of the assessment. In addition, relevant optional indicators from Annex A and Annex B were also selected to complement the analysis. This approach ensures a structured and standardized evaluation of key aspects such as material recyclability, resource efficiency, and environmental performance. After the selection and application of the circularity indicators, the results are expected to provide a clearer understanding of the products' circularity potential. Based on these findings, a subsequent LCA will be carried out to evaluate how the identified circularity aspects may influence the environmental impacts of the systems under study.

These methodologies prove to be valuable tools for assessing and improving the environmental performance of products, offering companies a practical framework for guiding future decisions towards more sustainable alternatives.

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