Originalarbeit

Elektrotech. Inftech. (2023) 140:605–613
https://doi.org/10.1007/s00502-023-01181-x

e+i elektrotechnik und informationstechnik

Analyzing the environmental impacts of a 145 kV GIS over its complete lifecycle

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Received: 16 August 2023 / Accepted: 1 October 2023 / Published online: 8 November 2023

Abstract High-voltage switchgears are a vital equipment to ensure the grid operation, whose impact on the environment can be calculated with a Life Cycle Assessment. Removing SF_6 helps to reduce the carbon footprint of the switchgear but it usually deteriorates the other impacted categories.

This work compares the impact of two 145 kV GIS: one based on SF_6 and one with a C4-FN-based mixture as insulating and arc-extinguishing media. Using a C4-FN mixture, the footprint of the equipment is mostly reduced to manufacturing emissions and electricity consumption in service. The limitation of the mass increase appears to be key to minimize all environmental impacts, including the effect on climate change.

Some parameters of the assessment are also discussed to highlight the variability of the results depending on the user's requirements, even for a given layout, e.g., due to the low-voltage and instrument transformer specification.

The use of recycled or recyclable material is also distinguished. Both are very important, however, only the first one really reduces the carbon footprint of the solution. The evolution in the coming decades of the electricity generation mix is also discussed and cannot be considered in the calculation. Overall, the manufacturing phase should consider real figures and avoid double counting.

Keywords LCA · SF_6-free · GIS · Losses · Recycling

Analyse der Umweltauswirkung einer 145-kV-GIS über ihren gesamten Lebenszyklus

Zusammenfassung Hochspannungsschaltanlagen sind wichtige Betriebsmittel zur Sicherstellung des Netzbetriebs, deren Auswirkungen auf die Umwelt mit einem Life Cycle Assessment berechnet werden können. Der erwünschte SF_6-Ausstieg trägt dazu bei, den CO_2-Fußabdruck der Schaltanlage zu reduzieren, kann jedoch zu einer Verschlechterung anderer Kenngrößen führen.

Diese Arbeit vergleicht den LCA von zwei 145 kV-GIS: eine basierend auf SF_6 und einer Lösung mit C4-FN als Isolier- und Löschmedium. Durch den Einsatz einer C4-FN-Mischung wird der Fußabdruck der Anlage größtenteils auf die Herstellungsemissionen und den Stromverbrauch der GIS im Betrieb reduziert. Die sehr guten dielektrischen Eigenschaften der C4-FN-Variante erlauben es, GIS mit denselben Dimensionen sowie nahezu identischem Materialbedarf und Masse zu bauen. Dies ist der Schlüssel zur Minimierung der Umweltauswirkungen, einschließlich Einfluss auf den Klimawandel.

Einige Parameter der Berechnung werden ebenfalls besprochen, um die Variabilität der Ergebnisse in Abhängigkeit von den Anforderungen des Benutzers hervorzuheben, selbst für ein bestimmtes Layout, z. B. aufgrund der Niederspannungs- und Messwandlerspezifikation.

Auch die Verwendung von recyceltem oder wiederverwertbarem Material wird unterschieden. Beides ist sehr wichtig, aber nur recyceltes Material verringert wirklich den CO_2-Fußabdruck der kompletten Lösung. Die Veränderung des Stromerzeugungsmixes in den kommenden Jahrzehnten wird diskutiert, darf aber in die Berechnung der heutigen Produkte nicht einflie-

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ßen. Insgesamt sollten in der Herstellungsphase reale Zahlen berücksichtigt und Doppelzählungen vermieden werden.

Schlüsselwörter LCA · SF_6-frei · GIS · Verluste · Wiederverwertung

1 Introduction

The energy sector has seen increasing demand over the last decades and electricity generation had a moderate rate of rise in well-electrified regions, and mostly extended in developing countries. However, unprecedented changes are expected due to the transition out of fossil fuels which requires to quickly increase renewable energy electricity generation and the consequent transmission network [1]. Simultaneously, the equivalent greenhouse gas (GHG) emissions of the installed equipment should be minimized to ultimately achieve a net-zero society.

In the EU in 2009, 28.4% of the consumed primary energy was lost before reaching the end customer, including 1.4% from electricity transmission and distribution losses, 5.0% due to the energy sector's own consumption, and 22.0% due to the power transformation losses [2]. High-voltage switchgear are relatively low contributors to the total footprint of our energy consumption. However, they still have an environmental impact, as highlighted by the increasing SF_6 concentration in the atmosphere [3]. Manufacturers have been working to reduce that impact while ensuring the necessary reliability and large demand of the grid operators. This particularly applies to situations where known GHG are used in large quantities. This is specially the case for GIS (Gas-Insulated Switchgear) which use a large volume of compressed SF_6 in most applications today.

With the main objective to reduce the carbon-footprint of their equipment, switchgear manufacturers have been working during the last decade to replace SF_6. Finding alternatives to the exceptional insulation and interruption properties of SF_6 is a challenging task. Interruption in vacuum has demonstrated limitations at 145 kV and above and is only applicable to circuit-breakers. New alternative insulation and interruption media have emerged, especially C4-FN mixtures [4], which particularly grew in the last years.

C4-FN mixtures designate mixtures of C_4F_7N (C4-FN), O_2 (optional) and CO_2 or N_2. C4-FN is providing high dielectric properties [5], O_2 reducing conductive by-products and slightly improving the interruption performance [6], and CO_2 is the carrier gas, ensuring a low dew temperature, and decent insulating and interrupting properties [7]. N_2 could be used as an alternative carrier gas mostly in applications where no switching is required because it has a very low interrupting performance.

Unlike synthetic air, CO_2-based mixtures are providing decent switching performances, which allows an easier replacement of SF_6 in disconnecting and earthing switches [8]. Unlike vacuum circuit-breakers, gas circuit-breakers using CO_2-based mixtures are scalable to high voltages. C4-FN mixtures combine this advantage with the greater dielectric properties given by C4-FN, avoiding the size increase compared to SF_6 products. With the addition of O_2 greatly diminishing solid by-products [9], applications to higher voltages are also facilitated.

This paper investigates the environmental impacts of two GIS solutions, one using SF_6, the other one using a C4-FN mixture. The objective is to see how the replacement of SF_6 reduces the total carbon footprint and to understand the side-effects of this change on other environmental criteria, and the perspective to further improve high-voltage switchgear.

2 Life cycle assessment (LCA) of a 145 kV GIS

2.1 Scope and methodology

An environmental life cycle assessment (LCA) is the most appropriate methodology to fully evaluate the impacts of a product on our environment [10]. With its cradle-to-grave approach, it accounts for all the stages of the life cycle of the equipment, providing an exhaustive analysis of the environmental footprint, including the manufacturing, installation, use and end-of-life phases.

This study is based on a most recent and in depth LCA of a full 145 kV GIS. A typical double busbar line-bay layout is considered, including busbar disconnectors, circuit-breaker, current transformer, line disconnector, make-proof earthing switch, voltage transformer, cable box for cable terminations, and all their respective operating mechanism and wiring inclusively a local control cubicle.

Two versions of this GIS are considered (Fig. 1). One is using SF_6 as medium for insulation and interruption, the second uses a C4-FN mixture. The C4-FN mixture is defined as 6% C_4F_7N, 5% O_2, 89% CO_2. Both products were introduced on the market in 2014 and 2017 respectively. Since 2017, over 400 C4-FN-based GIS bays have been sold, representing more than 40 substations in whole Europe. Since 2018 several substations in the grid of major European distribution & transmission utilities are energized or in the stage of installation and commissioning.

Despite its relative youth, C4-FN took off quite well in Europe and Korea. Several other solutions from various manufacturers have been presented, covering AIS, GIS, and Dead-Tank up to 420 kV.

Both solutions are very similar, although the C4-FN solution presents a slightly increased total weight mostly due to changes in the circuit-breaker (height and internal parts) and fast earthing switch (internal parts). The split of the total mass of each GIS according to the IEC 62474 standard is presented in the Fig. 2.

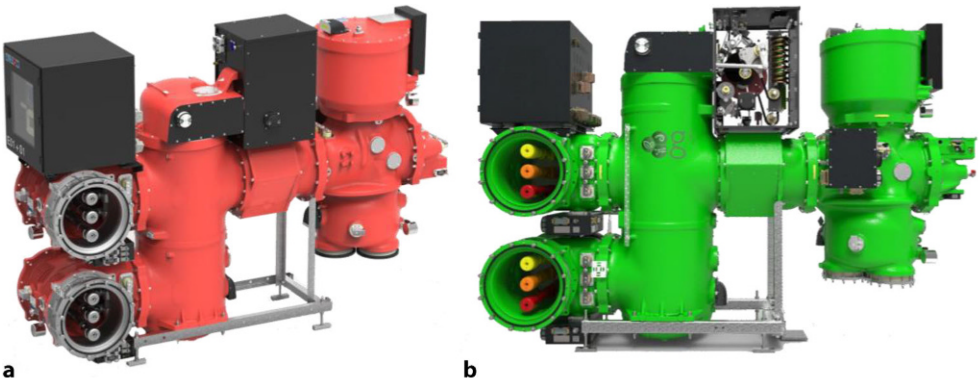

Fig. 1 Considered 145 kV GIS using a SF_6 (**a**) or C4-FN mixture (**b**) for insulation and interruption. Both have the same overall dimensions (width, length, height)

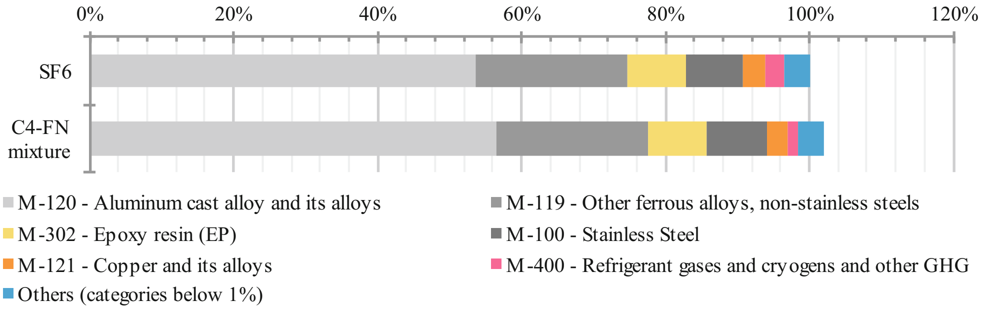

Fig. 2 Main materials used in the GIS for each solution

Each part is modelled based on its raw material use, transformation processes, and average transport distance, accounting for the country of manufacturing, material losses, processes consumptions, and packaging. Assembly in the GIS factory and factory testing are also considered based on yearly factory's impacts.

The installation includes the use of equipment, material, travel to site, and 1% of gas loss (conservative value assuming some minor release during gas handling). However, the impacts of the use of on-site testing equipment (e.g., test transformer) is excluded from the scope of the study.

Delivery of the product to the customer (distribution) is represented by a 3500 km transport by lorry in Europe and additional packaging material.

The use phase includes the transmission of an average current of 875 A during the year, the energy consumption of the auxiliary equipment (anti-condensation heaters, losses in the local control cubicle). The considered losses in the instrument transformers are limited to the secondary windings and a short length of cable, while user-side possible losses discussed in the paragraph § 3.3 are not included. Refills of gas, including the crew transport, are included. The annual leakage rate considered is 0.1%/y for SF_6 and 0.5%/y for the C4-FN mixture (in correspondence with the limits defined in the IEC 62271-203:2021).

The end-of-life phase includes the dismantling, scraping, and transport to processing plants. Recycling cannot be included in that phase as explained in the paragraph 3.4.

The physical dimensions and mass of the GIS have a direct impact to the building size and therefore a significant impact to amount of construction materials used to build a full substation. A complete system-wide analysis would show the results. This is not accounted for in this study, which excludes all components outside of the GIS and the building.

For the electricity consumption, the entire Europe region is considered (EcoInvent database), therefore probably near 238 $g_{CO2/kWh}$ (EU-27, 2021 [11]).

The analysis was performed with SimaPro LCA software version 9.4.0.2. The calculation method used is PEP EcoPassport ed4 Ev-DEC 1.09 ei3.8. The analysis is in accordance with PEP EcoPassport Program's PCR, ed4-2021-09-06.

2.2 Reference results with SF_6

The results of the LCA for the SF_6 GIS are shown in the Fig. 3 for each indicator and highlighting the contribution of each phase. The manufacturing and operation & maintenance phases are the most impacting phases for this scenario.

LCA studies the various environmental impact of a product, as listed in the Fig. 3. Some analyses include an overall score obtained by weighting the various indicators. Such grading of impacts is possible, but challenging because it implies to rate the environmental priorities. Common or industrial references are useful to determine how the product is performing in absolute for each category, especially uncommon ones.

For the considered case, the GIS is having a total carbon footprint (climate change indicator) over 40 years of 297.3 $t_{CO2\text{-}eq}$. Assuming the GIS is operating at 132 kV, it transmits up to 70.15 TWh over 40 years, so around 4.24 $g_{CO2\text{-}eq}/MWh_{transmitted}$.

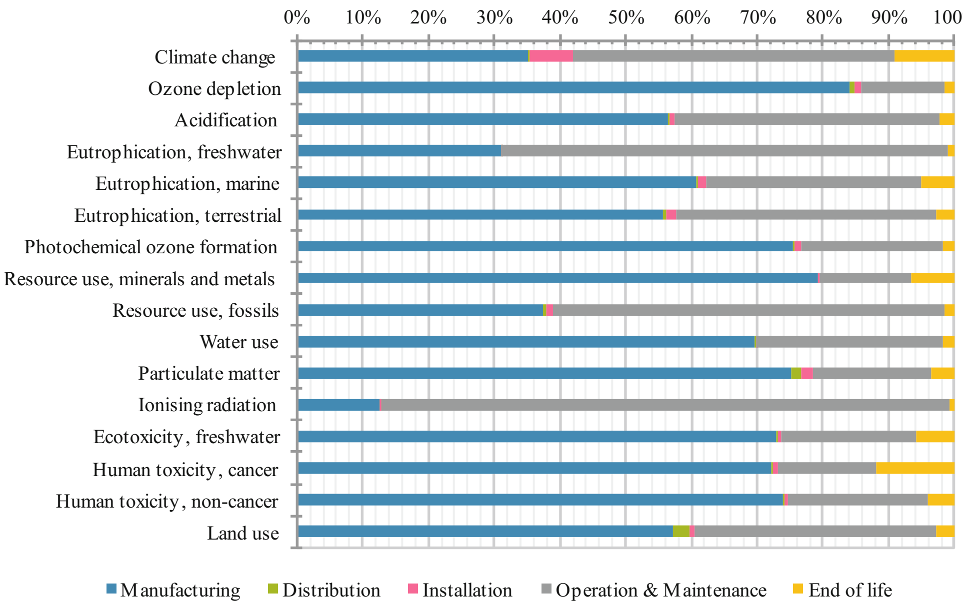

Fig. 3 LCA indicators obtained for the studied 145 kV SF_6 GIS

2.3 *Reference results with a C4-FN mixture*

2.3.1 Expectations

Using a C4-FN mixture for insulation and interruption is very efficient at reducing the carbon-footprint of a high-voltage switchgear. Indeed, the GWP_{100} of SF_6 is 24,300 and 2750 for pure C4-FN [12]. In this application, the GWP of the mixture is therefore 640 due to the low amount of C4-FN. Additionally, as the filling gas density is much different, with around 39.6 kg/m^3 for SF_6 and 19.9 kg/m^3 for the C4-FN mixture respectively. Overall, the carbon-footprint of the gas is reduced by 99% when replacing SF_6 by a C4-FN mixture in the presented situation.

The carbon-footprint of the production of gas is also improved by replacing SF_6. Calculated at 136 $kg_{CO2\text{-}eq}$ per kilogram of liquefied SF_6, it is reduced to 10.2 $kg_{CO2\text{-}eq}$ for the considered C4-FN mixture. This reduces the climate change impacts of the manufacturing phase. More significative is the removal of the SF_6 gas losses during the assembly when using C4-FN mixtures. In total, 20.8 $t_{CO2\text{-}eq}$ are from SF_6 in the manufacturing phase.

The installation phase is responsible of 19.36 $t_{CO2\text{-}eq}$ in total in the studied SF_6 case. 17.47 $t_{CO2\text{-}eq}$ is due from the SF_6 leak (1% of total) during gas handling. By using C4-FN, the same leak would only be 0.25 $t_{CO2\text{-}eq}$, reducing by 89% the carbon footprint of that phase.

The use phase is most significatively improved by using C4-FN mixtures instead of SF_6 (0.1%/year and 0.5%/year assumed for the SF_6 and C4-FN leak respectively). Around 1.5 $t_{CO2\text{-}eq}$ is saved each year due to the 99% CO_2-equivalent reduction of the gas. The electrical losses during the use phase are the same in both scenarios, with a total of 172 MWh. 47.4% of losses come from the main high-voltage circuit (with 875 A yearly average), 47.5% is due to the anti-condensation heaters, and the remaining 5% is due to the instrument transformers (considering the assumptions detailed in § 3.3).

At the end of life of the equipment, another 1% gas loss is estimated, representing 85% of the emissions associated to that phase (27.1 $t_{CO2\text{-}eq}$ in SF_6) that are not-present at this high level when using C4-FN instead of SF_6.

2.3.2 Overview and comparison with SF_6

The LCA results of the GIS using a C4-FN mixture are directly compared with those of SF_6 and presented in Fig. 4, where 100% represents the score of the SF_6 GIS. The replacement of SF_6 by a C4-FN mixture drastically reduced the climate change impact of the GIS (–41.2%, 122.3 $t_{CO2\text{-}eq}$), moderately increased the ozone depletion indicator (+23.0%, +0.0072 $kg_{CFC11\text{-}eq}$), and kept only remotely affected the others (–0.7 to +3.1%).

In the Fig. 5, a breakdown of three categories of interest is presented:

- Climate change (GWP): Using C4-FN significatively reduced that phase. What is remaining is in majority due to Joule losses in the high-voltage circuit, consumption of the LV equipment, losses in the secondary windings of the transformer voltages and cables. As the manufacturing phase is also reduced (no SF_6 leaks), the global warming potential of the C4-FN-based GIS is much reduced.
- Ozone depletion: The higher transient pressure in the interruption chamber of the circuit-breaker when using alternative gases [7] required to reinforce the PTFE nozzle, which is the main contributor to the ozone depletion potential (ODP). The absolute value remains small, with approx. 0.034 $kg_{CFC11\text{-}eq}$.
- Resources used, fossils: The criterion shows a very minor increase corresponding to the increase of

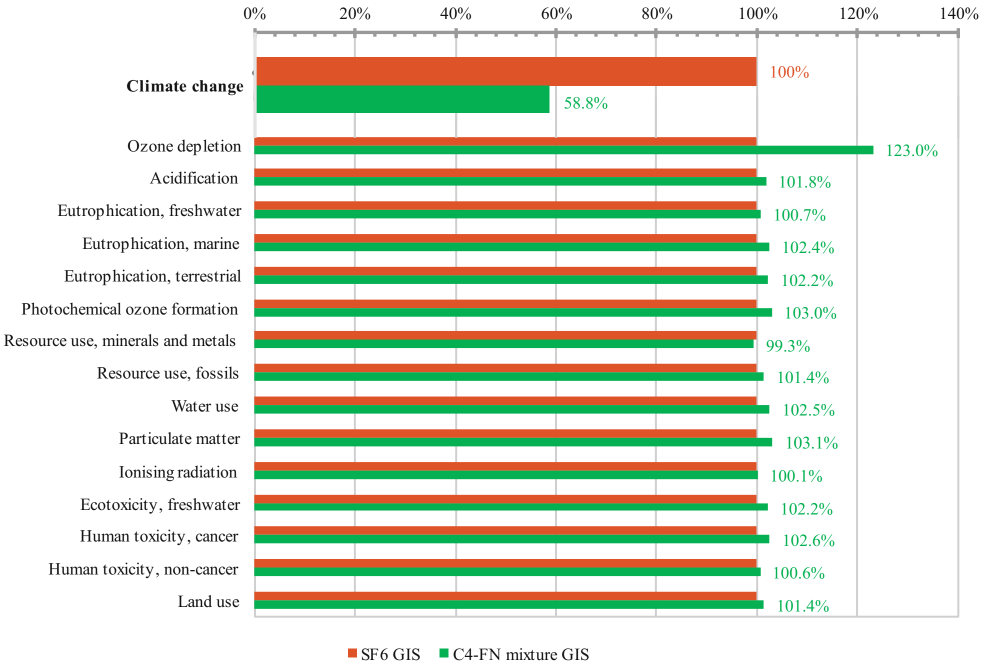

Fig. 4 Comparison of LCA indicators obtained for the studied SF_6 and C4-FN 145 kV GIS

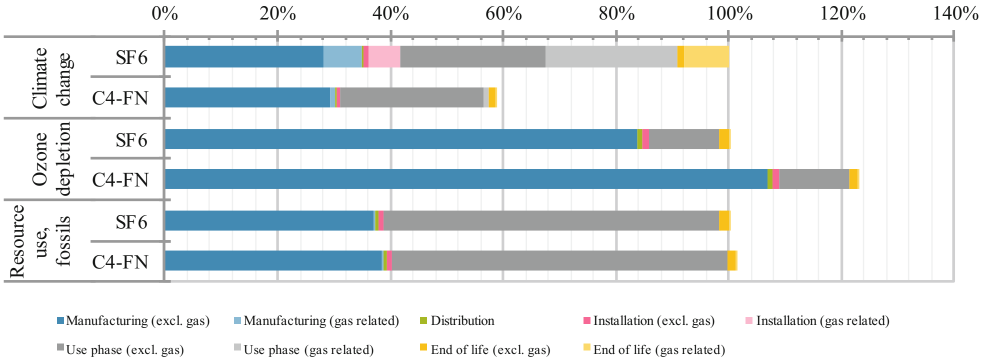

Fig. 5 Detailed results of the SF_6 and C4-FN-based GIS on key impacts categories

mass of the switchgear. This increase is minimized with C4-FN mixtures as they permit to keep closest to SF_6 dimensions and weight than any other SF_6 alternative. Similarly, the non-fossils resources (minerals and metals) are not increased when replacing SF_6 with a C4-FN mixture.

3 Discussion

3.1 *Impact of the equipment's mass*

As presented in the results and visible in Fig. 5, the mass of the equipment is closely related to the total environmental impacts of the switchgear. It even becomes dominant for SF_6-free switchgear, as the gas contribution drops to minor levels (1.8% of the total GHG emissions). Maintaining a low total mass is of major importance to minimize all indicators, including the climate change.

It is visible in Table 1 that, for a same functions and performance, the mass of the switchgear can vary a lot, with certain impact on the environmental indicators. More importantly, depending on the chosen alternative to SF_6, the increase of mass compared to the SF_6 reference can be very different. The mass and dimensions of the switchgear will also require stronger and larger buildings consuming significantly more construction materials and require larger air conditioning systems. This major impact does not appear in the LCA results of the equipment alone.

The selection of the medium to replace SF_6 for insulation and interruption can have an important effect on the manufacturing phase of the product and mitigate the gains from the gas replacement itself.

Table 1 Masses of different 145 kV GIS as declared by the manufacturers

	Studied case	Supplier B [13]	Supplier C [14]
Reference solution	2.6 t (SF_6)	3.3 t (SF_6)	4.5 t (SF_6)
SF_6-free solution	2.7 t (C4-FN)	3.7 t (C4-FN)	6.0 t (synthetic air)

3.2 Losses in the low voltage equipment

Different types of low-voltage (LV) components are used in a GIS. Anti-fogging heaters are easily accounted for and present in the operating mechanism cabinets and the local control cubicle (LCC), representing quickly over 100 W. However, the main challenge is to estimate the losses of the numerous LV components of the LCC.

The documentation provided by the components' suppliers may not include the consumption or losses in service conditions and must be extrapolated from similar equipment. Service conditions are also not easily assessed.

More importantly, the LCC configuration and wiring is strongly project specific. Depending on the specification, the number and type of LV components under voltage is changing. Using the bill of material is not sufficient, and only the components active permanently must be considered (e.g., closed switch).

Especially, the following applies:

- Conventional LCC will have higher power consumption than digital solutions, with 50–200 W and 50–70 W ranges respectively in typical cases.
- A conventional solution can be very economic when using minimum monitoring and normally-open (NO) contacts where possible. In such situation, only a few components are energized, and total power is low. However, the use of "fail-proof" normally-closed (NC) contacts drastically increases the used power (~5 W per relay, plus contacts, plus cables).
- Depending if the LCC is mounted on the bay or standalone then the size and the consumption is different. Even the anti-fogging heater is different.

Normal cases stand between 50 W and 200 W. However, extreme cases can go over 350 W. For this study, a realistic value of 100 W has been considered, with 20 W on top for the anti-fogging heater.

3.3 Losses within instrument transformers

Losses on the primary and secondary sides of instrument transformers can be estimated based on the configuration of the GIS. In the case of the current transformer, the primary side is considered in the main circuit Joule losses.

The energy consumed by the instrument transformers is strongly depending on:

- *Number and characteristics of the installed windings.* Each winding consumes energy due to Joule losses of the wire. These are typically in the range of 3 to 8 W per winding for a current transformer and around 2 to 6 W for a complete voltage transformer for example. This is different from the admissible burden by the instrument transformer while maintaining its accuracy, itself normally higher than the real permanent load in service.
- *Actual average burden on the transformers, including the electronics and cables.* This is theoretically outside of the GIS manufacturer scope but could indirectly be taken from the required burden. However, assuming the full burden permanently is strongly unrealistic. For the presented study, the consumption outside of the GIS is excluded, so the burden on the user side must be added to the presented results.

For the presented study, losses of 36 W are accounted for the current transformer, assuming three measurements per phase and considering only the GIS scope. Such configuration is usually capable of rated burdens of 100-200 VA in total. For the voltage transformer, 5 W of losses are considered within the GIS scope, to be compared with a rated burden in the range of 45–150 VA (two winding per phase).

These losses are small contributions at the grid scale, but can make a few percents difference when comparing two switchgear with the same functions but different hypotheses of load.

3.4 Considerations of recycling

The use of resources is accounted for in the LCA through different inputs and outputs.

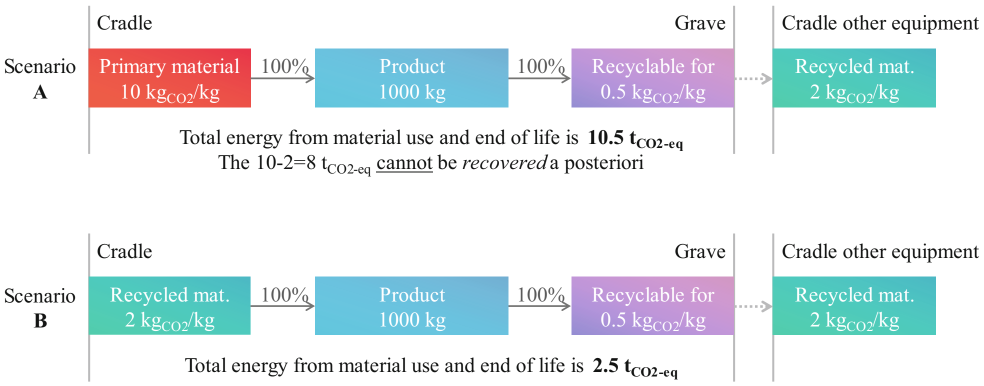

Fig. 6 Recyclability example scenarios to highlight the difference between using recycled material and using recyclable material

- The use of recycled content leads to lower emissions in the manufacturing phase.
- The recyclable material must be processed at the end of life of the equipment. However, this is still negatively impacting the LCA because it requires energy to be dismantled, scrapped, and brought to the recycling facility.

Having material to be recycled at the end of life of the equipment does not allow to offset some CO_2-equivalent emissions because the reduction applies also for the ones using the recycled content. This is highlighted in the Fig. 6 by showing that the recyclability of the used material is very different than using recycled material. This could have been partially accounted for in cradle-to-cradle LCAs or through the material circularity indicator (MCI), but they are not very adapted to the long lifetime of high-voltage switchgear. Although there is no CO_2 compensation of the material to be recycled, it has usually a financial value.

3.5 Influence of the GHG intensity of electricity generation

With the integration of more renewable energy sources for electricity generation, the carbon footprint of consumed electricity is expected to go down to a fraction of its actual level. Although this change will take 30 years or more, the long service life of the equipment makes such considerations senseful.

However, this is not yet integrated in the calculation presented above because it is not possible to know how the carbon intensity will evolve. Therefore, such considerations can be implemented for information only, and estimations were already presented for this GIS [15].

Overall, it is important to understand that the transition to a low carbon intensity of electricity generation will only moderately affect the use phase of the equipment. The manufacturing phase, happening now and representing the biggest contributor to the environmental impacts of the equipment, is to be calculated with present emissions of the processes. In an LCA, the energy flux must be followed, and not the financial ones. The LCA core principle is that double counting must be avoided, thus e.g., contracts for renewable energy supply do not reduce the carbon footprint because their contribution is already accounted for at a regional level and accounting it for at a customer level would lead to double counting. These are very important points to investigate to avoid inaccurate results that are not in line with the standards [16].

4 Conclusions

The work presented shows that the environmental impacts of a 145 kV GIS are mostly due to the manufacturing, operating and maintenance phases.

For the climate change impact, replacing SF_6 with a C4-FN mixture reduces the contribution of the gas by approximatively 99%, leaving mostly the manufacturing phase and the electrical consumption of the equipment as main impacts.

By keeping a minimum mass and similar materials, the C4-FN solution achieves a significant carbon-footprint reduction (–41.2%, 122.4 $t_{CO2\text{-}eq}$) and avoids large impacts in other categories. Only the ozone depletion potential is moderately increased due to the increased use of PTFE. However, the absolute quantity of PTFE is very low (SF_6 and C4-FN have a ODP of 0).

The C4-FN-based GIS weights less than 100 kg more than the previous SF_6 GIS (totally 2.6 t). This is why the use of C4-FN mixtures, despite their GWP, have a low and balanced environmental footprint. Using another insulation medium with lower dielectric and/or thermal properties such as synthetic air will lead to a direct increase of the environmental impacts. Especially the total weight and therefore material consumption seems to be significantly increased to a total bay weight of 6 t. Working to reduce the footprint of the manufacturing phase of products appears key to minimize the carbon footprint of the equipment. The study also demonstrated that the losses of the GIS, especially for the LV equipment and instrument transformer are very project dependent. These losses are not negligible in the total footprint of the considered equipment and can be dominant in some cases.

The proper consideration of recyclable and recycled material as per the standards is also important. Although both are relevant, only the (proven) use of recycled material actually reduces the carbon-footprint of a product. Using recycled material is an effective way to reduce the manufacturing phase impacts, especially when reducing the mass of the equipment is not possible anymore. The quantity of critical materials needed, like copper, is also of importance for secured and souverain supply chains but is not directly highlighted by LCAs. It appears that the choice of technology can strongly influence this value.

Similarly, although the extrapolations concerning the future electricity mix are relevant considering the long lifetime of the equipment, they cannot be applied to current times, and especially not to the manufacturing phase unless proven otherwise. There is a need for standardized rules in that regard. This works highlights the numerous parameters relevant to a LCA that should be discussed with the users and always fully described in the results. This allows the users to understand and check the presented results, and even possibly to update the specification to improve them.

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