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PS1 – Emerging Substation & HV equipment strategies to deliver the transition to a low carbon future

Guidelines and assessment methods for end users to estimate, quantify and challenge climate change and ecological impacts of medium- and high-voltage switchgear

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Summary

In the worldwide effort to limit global warming, the energy transmission and distribution system operators and switchgear manufacturers have been actively looking for medium- and high-voltage switchgear with a lower climate change impact. The first step of this process is the removal of SF_6, the most potent greenhouse gas (GHG), whose complete removal in switchgear will need many years, especially for the highest voltage and short-circuit ratings.

However, even SF_6-free equipment has a non-negligible impact on the environment, including on the climate change, which users will need to consider to minimize their carbon footprint.

This paper investigates common assessment methods of the environmental impact of a switchgear, to objectively estimate their carbon footprint in a way that can be used by grid operators at any step of a project, from within public tender phases to complete system wide LCA studies. It goes through GWP, LCA, and simplified estimations results and clarifies their scope, forces, and weaknesses, including the notion of time and avoiding greenwashing arguments. By involving different customers, specialists, and manufacturers, the comparison aims for fairness and mentions uncertainties and limits of the study.

It especially includes the feedback from two major European utilities, RTE and Stedin, which had different approaches to include environmental assessments in their strategy and decisions. Some key takeaways are presented along guidelines for accurate and comparable environmental assessments.

This work can only be the starting point of a renewed way to account for ecological impact of medium and high voltage switchgear. The paper ends with an open conclusion, inviting more scientific work to define the path to the low-carbon switchgear of tomorrow.

Keywords

Carbon-footprint, LCA, Environmental evaluation, Carbon-pricing, SF_6-free

1 Reducing the carbon-footprint of electrical substations

Huge efforts are needed to reach a carbon-neutral society by 2050. To sufficiently reduce the use of fossil fuels, the electrical grid needs to be expanded and upgraded considerably [1]. It is important not only to make sure that the electrical energy production comes from renewables such as wind or solar power, but also that the grid itself has high efficiency and low emissions, without compromising the reliability of the power supply.

To help with this work, Life Cycle Assessments (LCAs) can be done to estimate the environmental impacts of products and equipment over their complete lifecycle (cradle-to-grave). There are international standards for such assessments like the ISO 14040 series. Environmental impacts covered by the LCA methodology include potential impacts on climate change, ozone depletion, eutrophication, and acidification to name a few. Assessing several environmental impacts avoids problem shifting, meaning that impacts for linked to environmental problem increase, while aiming at decreasing another.

Most of today's medium and high voltage switchgear contain SF6, which is the world's most potent greenhouse gas (GHG) known, with a global warming potential (GWP) of 24 300 [2]. The technical properties of this gas ensure reliable control of the grid during normal and faulty conditions, but SF_6 also stands for a significant part of the grid owners' GHG emissions due to leakages during gas handling or in service (normal and abnormal leakages) [3] [4]. Consequently, grid operators, switchgear manufacturers, and policymakers are pushing to find alternatives that have less impact on the climate and environment, while making sure that the grid can still be safely operated.

Recently developed SF_6-free solutions all show significant CO_2-equivalent emissions reductions (40%-90% for high-voltage equipment [5] [6] [7]), but many other factors are also influencing the environmental impact of the equipment. When including all lifecycle stages for medium voltage equipment, reducing joule losses would be the most important strategy for reducing the impact on climate change [8].

If grid operators want to reduce their CO_2-emissions, they need to have methods to assess the carbon-footprint of their equipment that are scientifically correct and compatible with their processes.

This paper aims to investigate common assessment methods of the carbon footprint of switchgear. It approaches it from a grid-operator-perspective and evaluates the compatibility of the studied methods with their use in early project or tender phases. It goes through various carbon footprint methods and clarify their scope, forces, and weaknesses. By involving different customers, manufacturers and specialists, the comparison aims for fairness and mentions uncertainties and limits of the study. The goal of the paper is to provide advice for manufacturers, grid owners and policy makers, such that:

- Switchgear manufacturers can implement the right assessment methods to allow them to evaluate and possibly optimize the environmental footprint of their products and promote it.
- Grid owners can make knowledge-based decisions when selecting equipment for their substations with criteria regarding their carbon-footprint.
- Policymakers are made aware of the factors that influence the environmental impact of different switchgear technologies.

2 Review of climate change impact indicators

LCA studies cover several environmental impacts. The most commonly used is impacts on climate change, referred to as Global Warming Potential (GWP) and the unit is CO_2-equivalents. Different substances have different characterization factors, meaning that they have different potential impacts in the same impact category (see table 1).

In the medium and high voltage sector, GWP is almost always used to describe the characterization factor of the insulation gas only, for instance 24 300 for SF_6. To avoid confusion, this paper will use the term GWP only when referring to the characterization factor of the switchgear gas and use CO_2-equivalent for the other cases.

To keep the text concise, medium and high voltage network operators are also sometimes called utilities or users, and the equipment (switchgear) manufacturers, OEMs (original equipment manufacturers).

2.1 Literature and trustworthy results

There is more and more available literature that assesses the CO_2-footprint of medium and high voltage equipment, both SF_6 and SF_6-free solutions, and mostly through variants of LCA.

These studies rarely provide detailed cause-consequence information (where the impacts stem from). Some are limited to the climate change, others include all LCA's basic indicators (e.g., ozone depletion, acidification, etc.).

Previously, the comparison was typically between one SF_6 and one alternative solution [9] [10] [11]. However, with the development of alternatives, many new studies now compare one SF_6 solution to a couple of SF_6-free solutions [12] [13] [14]. In such cases, the comparisons might be flawed due to two factors:

- The unspoken objective is usually to show that the authors' solution is the best SF_6-free solution
- The second SF_6-free solution is usually not produced by the authors' company and data is estimated with high uncertainty.

LCAs certified by external companies ensure that the methodology has been reviewed. However, the data is still provided by only one manufacturer and not all details can be easily checked. In the case of extrapolation to another technology, a certified assessment does not guarantee that it is reliable.

2.2 Investigated assessment methods

A few common assessment methods of environmental impacts are investigated and compared below. These methods aim to summarize the environmental footprint / performance of one equipment in a quantifiable way that can be used for points attribution or decision making.

2.2.1 Limits based on GWP of the gas medium

The foremost indicator for switchgear has always been the GWP of the gas medium. It is this indicator that identified SF_6 as a major concern for the environment. The characterization factors are revised regularly by the IPCC (AR6 Chapter 7 Supplementary Material [2]). GWP values of common gases used in switchgear are given in the table below (gas only):

Gas	SF_6	C4-FN	C4-FN mixtures	C5-FK	CO_2	Air, O_2, N_2
GWP_{500}	29000	835	100-200 when mixed with O_2/CO_2	<1	1	0
GWP_{100}	24300	2750	300-700 when mixed with O_2/CO_2	<1	1	0
GWP_{20}	18200	4580	600-1100 when mixed with O_2/CO_2	<1	1	0

Table 1 - GWP (characterization factor) of common gases used for insulation and interruption in medium- and high-voltage switchgear in 500-, 100-, and 20-years perspective

Considering only the GWP of the gas medium is a very simple criterion but also very limited. It only indicates the impact of the gas itself relatively to CO_2 (for the same mass). It is not an environmental assessment method, and it ignores the installed mass (the amount of gas needed), density, or leakage rate. It also does not distinguish between a modern AIS with low emission rates (~0.1%/year, a few grams) and an old GIS emitting significant amounts (>1-2%/year, several tens of kgs).

GWP is an important criterion to identify which gases should be controlled and not released in the atmosphere due to their greenhouse effect.

However, it misses completely the actual emissions of gas and, moreover, the environmental impact of the equipment containing that gas. This simplification is demonstrated to be very incomplete when calculating properly the carbon-footprint through an LCA. It is even worse for SF_6-free solutions where the gas impact is lower relative to the total CO_2-equivalent emissions.

2.2.2 LCAs methods and PCR

LCA are detailed studies of the complete environmental impact of a product. They take into account the raw materials, how the product it made, transported and used, and what happens at the end of the product lifetime, as shown in Figure 1.

LCAs are much more detailed than any other analysis as they capture the whole life cycle of the product, and a large set of environmental indicators. The method is standardized, but depending on the scope of the study, there is freedom of interpretation. For external communication of LCA results, there is a need for specification of the calculation rules, for assuring comparability.

Product category rules (PCR) are required when LCA results aimed to be communicated, for instance in the form of Environmental Product Declaration (EPD) or a carbon-footprint. The results of different assessment methods are not comparable, as they follow different calculation rules [8] [15] [16].

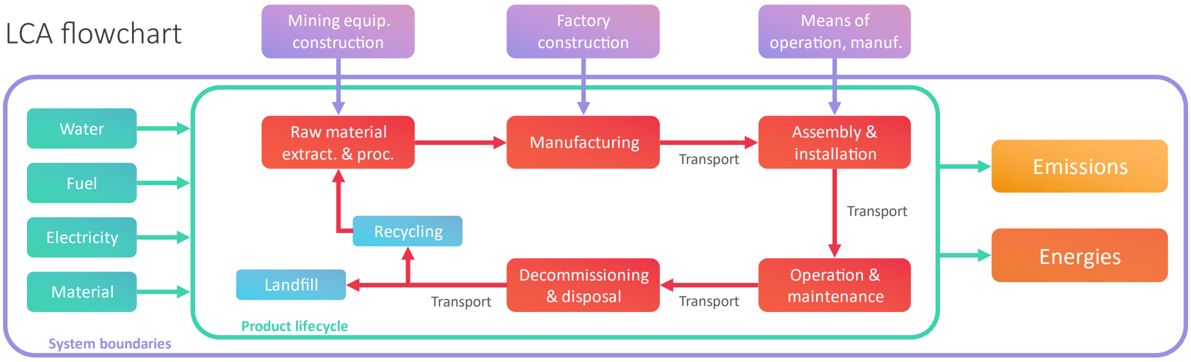

Figure 1 - Schematics of the LCA workflow (cradle-to-grave)

For the data accuracy and completeness, the study relies on the capacity of the OEM to get data for its complete supply chain (which may change), including transport and sub-suppliers sourcing. Tools are commercially available to help providing with a statistical approach but the number of parts in a switchgear represents a tremendous task.

Overall, care should be given to the following points when analyzing LCA results:

- The followed standards, for both the calculation itself (ISO 14044/ISO 14067) and the studied product scope (PCR is followed if available)
- is the presence of a third-party verification of the assessment and its assumptions
- The quality and assessment of the upstream and downstream data, and by whom the data is provided

2.2.3 Simplified estimations based on LCA concepts

Simplified estimations based on LCA concepts are sometimes used to assess the carbon-footprint of a product with a much-simplified scope and dataset. They are usually trying to focus on the few elements contributing more to the overall carbon-footprint of the equipment.

Usually, these are made within a spreadsheet that can be easily understood, consolidated, and completed by the contributors, network operator and equipment manufacturers alike.

Typical hybrid estimations include the following aspects:

- **Mass of material and associated factors** to be converted to CO_2-equivalent emissions. This factor determination is usually key as assumptions have to be made. All solutions are compared with the same factors, independent of the source or content or recycled material.
- **Transport**, when taken into account, is usually only from the final factory to the project site, ignoring the supply chain transport.
- **Estimation of leaked gas per year and use of GWP** to get to CO_2-eq. Additional losses due to maintenance are often only planned at the end-of-life.

- **Various sources of Joule losses** for a pre-defined load. Sometimes they are limited to the main circuit, but some include instrument transformers and low voltage losses too. Conversion to CO_2-eq is done assuming an energy mix (usually fixed).
- **End-of-life** is often ignored or only considers a gas emission due to likely losses from gas handling.

These hybrid estimations have been successfully implemented in some tender phases because they allow easily understandable calculations. They are intermediate estimations and allow great customization for the utilities. However, they come with intrinsic limits regarding scope, accuracy and comparison potential that complete LCA cover.

3 Authors' return of experience with assessment methods for environmental impacts

3.1 The main challenges

Utilities face many challenges when building, upgrading, or replacing a substation. Each project has its specificities and equipment selection already relies on many criteria (performance, homologation, costs, etc.). However, users are increasingly trying to integrate environmental assessments in their processes to reduce the overall footprint of their substations. If grid operators want to push for products with a lower environmental footprint, they have to be able to assess it, quantify it and integrate it in their selection process.

To compare solutions, utilities need LCAs made with the project's scope and assumptions, and same methodology for all OEMs. The results should be more detailed than the ones usually presented, to allow a good understanding of the various phenomena at play and hypotheses.

Another alternative is to rely on harmonized Product Category Rules (PCR) which defines the method, scope, requirements, etc. for the LCAs. The advantage of having a standardized or harmonized PCR, is that the OEMs will be more likely to have it available as it applies to more projects. As a PCR is very detailed and makes it possible to directly compare different LCAs. This is considered to compensate for possible differences between the PCR conditions and the project ones. If substantial differences exist (e.g., CO_2-footprint of the grid), the reference study may have to be adapted.

The use-phase of medium and high voltage switchgear can be relatively easily described by the grid operators. However, the cradle-to-gate phase is strongly relying on the OEMs and must be well covered by LCAs. This can be also considered by the utilities to adapt LCAs to their exact situation (energy mix, substation load), without deviating from harmonized PCR, but only by taking the cradle-to-gate and end-of-life results from LCAs.

For now, the IEC 62271-320 appears as a potential harmonized PCR, but it will not be published before mid-2024 and many projects will be awarded before it is finalized. Users can already familiarize themselves with LCA and PCR to accelerate its adoption when the standard will be released. On the other end, consultations on potential regulations on SF_6 and SF_6-free solutions will finish before this key element for environmental assessments. There may also be a need for a PCR for HVDC equipment as many new projects are expected in the coming years.

In the absence of clear PCR, comparison of LCAs of the same OEM can be done because they have similar assessment methods. However, direct comparisons of LCAs from different OEMs could lead to uncertainties (comparing apples with oranges).

Another problem resides in the reliability of the data. LCA rely on a lot of data from the OEM that cannot be easily checked. In that context, having an external review assessment generally increases the quality and trustfulness of the document.

The absence of standardized assessment methods of CO_2-footprint for different network components creates a lose-lose situation:

- Manufacturers have low interests at optimizing their carbon-footprint beyond SF_6 removal because they are not translatable into economical advantage.
- Utilities cannot favor solutions based on their actual environmental impact.
- Regulators are unable to efficiently enforce the transition to low-carbon equipment because of the absence of a clear assessment method to fix objectives.

3.2 RTE, France

RTE performed several considerable LCAs to evaluate and compare the environmental footprint of their substations. It is a part of the actions implemented by the company to drastically reduce its CO_2-equivalent emissions as part of its general commitment to limit climate change.

These LCAs were not specific to a project or a tender phase but based on typical substations at a system level and for different structure and technologies. It covered the switchgear, building, secondary equipment, runway, etc. The data was collected by RTE, and the assumptions are the same for all equipment, leading to fair conditions, but missing supply chain specifics.

In their conclusions, RTE could identify which kind of substation that had the lowest environmental impact for their need. The results were that SF_6 AIS in an optimized building had the lowest impact, followed closely by SF_6-free GIS and then SF_6 GIS and SF_6 AIS (outdoor) at the end.

This methodology used 6 different environmental indicators from the LCA, and an example of the results is given in Figure 2. The worst solution for a given criterion is scaled at 100%. Lower values are better (lower negative climate impact):

Figure 2 - LCA indicators retained by RTE for the comparison of 63 kV substations (different types and technologies)

The LCA results could also be combined to a unique value grouping 16 indicators, giving a (simplistic) grade to the solutions. In the above example: 601 p, 616 p, 475 p, and 512 p for the SF_6 AIS, SF_6 GIS, SF_6-free GIS #1, and SF_6-free GIS #2, respectively.

RTE used this study to define the company's priorities for future substations. It is not project specific but representative of their future substations. It is likely the more complete system-wide LCA reported today. RTE now has the necessary information to prioritize its actions and minimize the carbon-footprint for the next projects. However, this study is only the picture of a situation at a given time and changes in products, civil works' materials, etc. could change some conclusions.

RTE is also using this study as an argument to some proposed incoming regulations as they demonstrated that the GWP is not consistent with the results and therefore counterproductive.

3.3 Stedin, Netherlands

Stedin has committed to reduce its emissions (100% of scope 1 & 2 in 2030, and as much as possible on scope 3). As part of this task, they started to introduce some indicators of the environmental footprint of the equipment in their tender phase.

Stedin do not perform LCAs themselves and has preferred an internal, transparent, and controllable assessment method. It is in the category of the simplified estimations and although it is inspired by the LCA concepts, it is much more limited but also easily completed by all OEMs.

The calculation accounts for the mass of materials used, equipment transport, and Joule losses (main circuit only). These are then converted to CO_2-equivalents and later to costs through a fixed CO_2-price.

This methodology is admittedly limited but designed to be simple and later extended to cover more aspects of the products' emissions.

It is seen as a success because it was the first implementation of such assessments and could be used for tender phases. It showed that even without a complete system view, Stedin could effectively integrate some environmental factors in their processes.

3.4 Policymakers' important role

While a full restriction on the use of SF_6 in new switchgear appears to be a question of time only, many policymakers also push for further restrictions which are not based on internationally recognized assessment methods evaluating the overall environmental footprint of the equipment.

The uncertainties created by the policymakers and their proposals could delay the transition to an SF_6-free switchgear market and grid. Most utilities are eager to transition away from SF_6 but the uncertainties in which SF_6-alternatives will be allowed in the future could create a hesitation to go for the SF_6-free technologies already on the market. Any delays in the implementation of SF_6-free solutions could ultimately lead to more SF_6 being installed. Furthermore, in a transition time, the "free market competition" might be compromised as only one or a few switchgear manufacturers can offer an SF_6-free alternative.

It is important that utilities show to their policymakers how they can quickly reduce their CO_2-footprint, while at the same time upholding the reliability of the grid. This starts by appropriating the data, hypotheses, and results of system-wide life cycle assessments, as per IPCC and EU guidelines which mention that "Life Cycle Assessments provide the best framework for assessing the potential environmental impacts of products currently available" [17].

4 Proposed guidelines

Most of the focus in the current and upcoming regulations is on the carbon-footprint of the equipment as this paper does. However, LCAs provide more information on other environmental impacts that are also of major importance.

4.1 Preferred assessment method

Authors agree that the best assessment method is:

1. Comparison of externally-certified LCAs done using a harmonized PCR: (e.g. IEC 62271-320) LCA should be done to compare the environmental impact of switchgear. These assessments must be done with defined and agreed-on Product Category Rules (PCR) which fully define the scope, and method to be used, allowing a truly reliable and high-quality comparison.
   For medium and high voltage switchgear, a harmonized PCR is still in-work in the IEC (TC 17) and the IEC 62271-320 standard is expected to be released mid-2024.

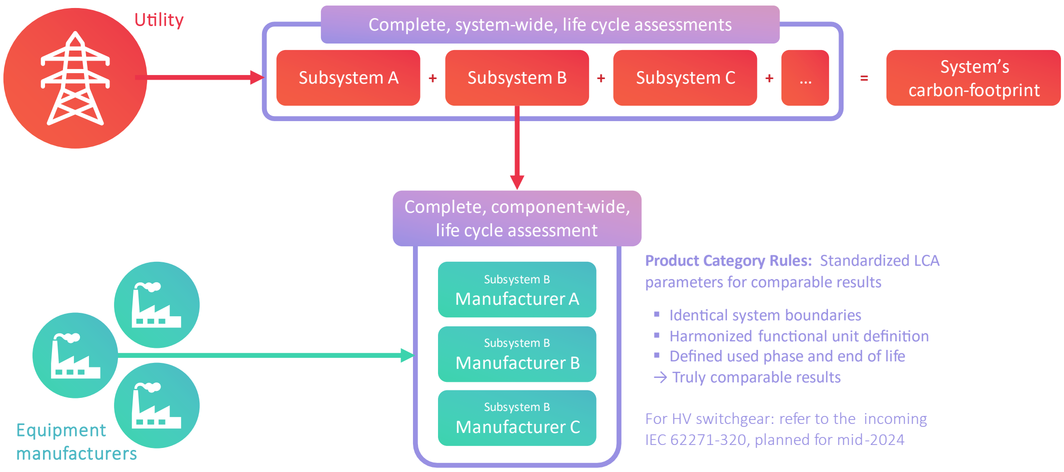

Figure 3 – Visual representation of the workflow for assessment of the environmental footprint of a system (e.g., substation)

4.2 Alternative assessment methods

Alternative methods as fallback in case the preferred one is not achievable in the project scope:

2. In case of detailed LCAs available but not in accordance with a harmonized PCR:
   The OEMs should collaborate with the utility to understand and quantify the gap with the desired PCR. Estimations can be made to correct an existing LCA and submitted to the utility which can then consider it in its comparison after validation.

3. In the absence of complete LCA or possibility to adapt or update an existing LCA to a harmonized PCR:
   Alternatively to a proper LCA, simplified estimations may be performed focusing on the main contributors of the environmental impacts of an equipment.

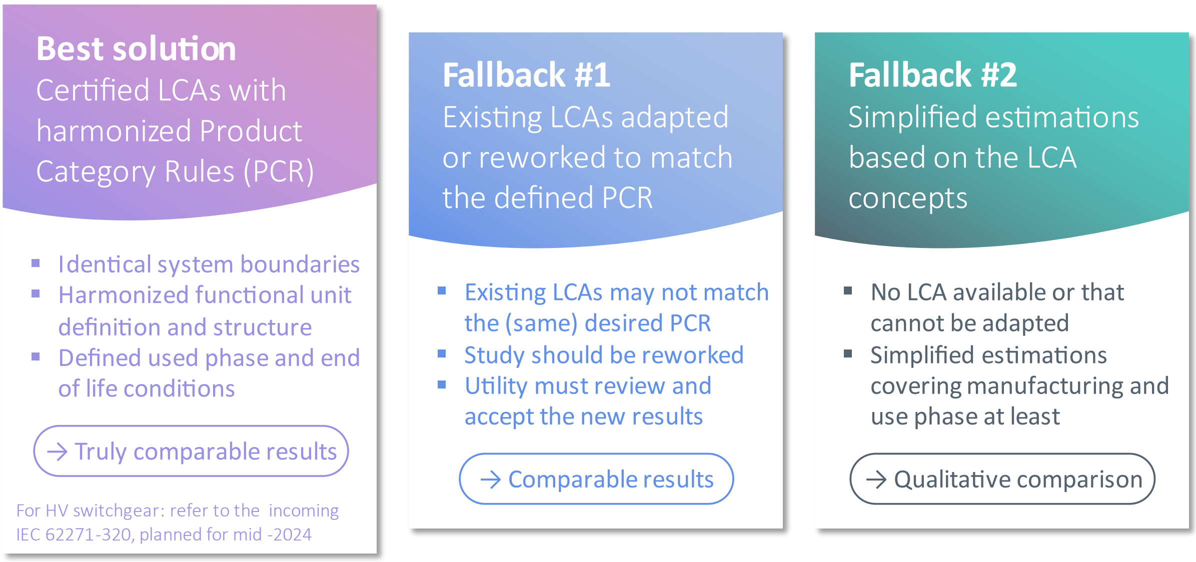

Figure 4 - Preferred method by authors and two identified fallback options for the CO_2-footprint assessment

4.3 Inadequate or incomplete assessment methods

The following assessment methods are not recommended because of their poor capability to evaluate the environmental impact of the equipment qualitatively and quantitatively:

- The GWP of the gas itself is not a sufficient criterion to evaluate the carbon-footprint of the equipment, nor to compare different products. The GWP of the gas does not consider the mass or volume installed, nor what is leaked over the equipment's lifetime. It is a good indicator to know if the gas can be released in the atmosphere, assuming other toxicological and environmental impacts are null or within admissible limits defined by local regulators.
- The CO_2-equivalents of the installed or leaked GHG during service and maintenance of the equipment, as it only covers a fraction of the use phase emissions and completely neglects the other phases, such as the production phase.

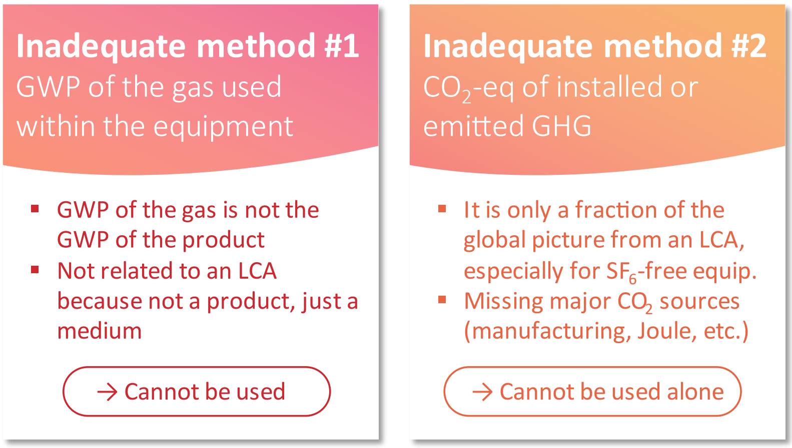

Figure 5 - Inadequate assessment methods for the evaluation of the carbon-footprint of an equipment

4.4 Valuation

The valuation method designates here the process to convert the estimated CO_2-footprint into a value or criterion used by the utility in the selection process.

Two important aspects should be considered:

a. How is the environmental footprint converted
b. How can it be integrated in the selection process

The utilities contributing to this paper had different approaches:

- Stedin used the total estimated CO_2-footprint of the product. The CO_2-equivalent is multiplied by a pre-defined CO_2-price (100 €/t_{CO2}). The CO_2-price does not consider the time of emission but is frequently re-evaluated (150 €/t_{CO2} in 2023). The total CO_2-costs are then added to the solution price, being a sort of CAPEX.
- RTE had a time-dependent approach to the problem. The objective was to reduce more and more the CO_2-footprint of the grid. Therefore, CO_2 emissions in 30 years are considered to be worse than those emitted today. The variable value of CO_2 was based on a recognized evaluation for France (Quinet II). The CO_2-emissions are therefore more like OPEX as they are spread over the service time.

The second approach is probably closer to the actual objectives of the grid operators because the installed equipment will be in service for a very long time. It is particularly severely impacting the SF_6 solutions which have the highest emissions due to the use phase. The definition of the variable CO_2 price should rely on national or international studies. As LCA studies can split the emissions by phase, such distribution can also be done by utilities based on a normal LCA report.

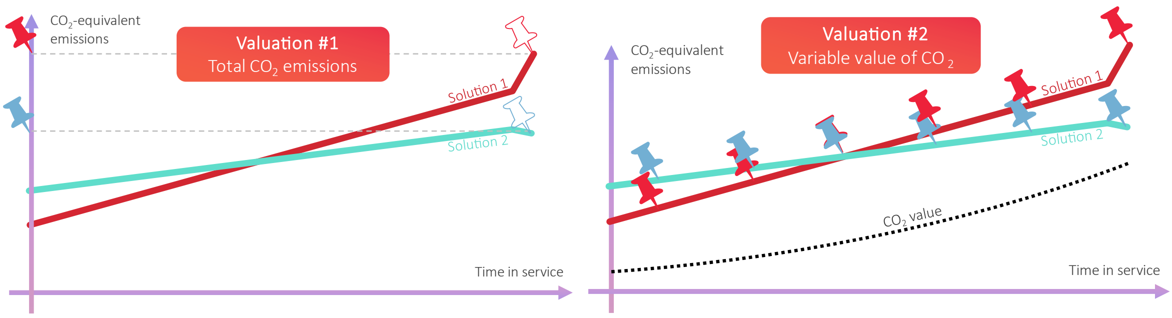

Figure 6 - Assumptions of fixed and variable CO_2-price considered by the authors (utilities) in their studies

4.5 Limitations

LCA are based on extensive work to evaluate the impact of each assembly, sub-assembly, and individual part, up to the manufacturing process and material. An LCA must be properly coupled with a PCR to ensure peer-reviewed conditions and comparison with other studies. They are considered the best assessment methods to determine the environmental impacts of a products as recognized by the EU [17] and are the basis of all IPCC reports.

Nevertheless, LCAs have their own limits. A significant one is the dataset from the OEM, itself relying on a complex supply chain. This is usually countered by the use of statistics, especially for the raw material provenance or machines consumptions. More general parameters like the load or actual leakage rates are more accurate when based on field experience. For the calculations themselves, commercial software is available to provide general support and such studies are usually performed in collaboration with specialized consultants to obtain certified and high-quality results.

Simplified estimations like presented above can only be less accurate than real LCAs. They miss an important number of points as highlighted before. Many unknowns especially lie in the supply chain and sub-suppliers' processes and prevent possible differentiations done by the OEMs. They cannot replace a proper LCA but offer a preliminary screening, especially useful in the absence of LCAs.

5 Conclusions

This paper investigated several assessment methods that can be used to evaluate the environmental footprint of medium and high voltage switchgear. It looked particularly at the assessments of the carbon-footprint and showed that they are key to identify and reduce the major sources of emissions.

It is shown that indicators limited to a fraction of the lifecycle, like the GWP of the gas or the gas emissions, are not adequate. RTE's system-wide LCA results confirmed that by showing that lowest GWP solutions were not always the least impacting at a product- and system-level, as major CO_2-equivalent emissions are from the manufacturing phase, especially for SF_6-free switchgear.

The authors conclude that the use of certified lifecycle assessments following harmonized product category rules (PCR) is the best solution to compare the environmental impacts of different products. In the lack of a PCR like the future IEC 62271-320, authors provided guidelines on the best fallback methods that can be implemented. With cradle-to-gate emissions covered with a proper LCA based on a defined PCR, utilities can even adapt the use phase and end-of-life emissions (gate-to-grave) to their specificities (energy mix, substation load) and have very accurate CO_2-equivalent emissions in time.

Two utilities also shared how they integrated the carbon-footprint results in their selection processes of equipment. They used different methods, but both were introducing a CO_2-price that then impacted the competitiveness of the solutions through CAPEX and OPEX.

In March 2023 the EU Commission proposed a directive on green claims that calls to end greenwashing [18] and performing LCAs completely fits the approach recommended by the directive.

As more and more entities are pushing towards a climate-neutral society, it is urgent to implement the right assessment methods and guidelines to understand where the CO_2-equivalent emissions are and how to reduce them. This paper aimed to show that such methods exist today and will soon improve further with the standardization of PCR.

To further reduce the emissions from the grid, more contributions from utilities are required, with detailed studies of the system and use phase contributions so that the manufacturers can address these. These studies should be based on the principles described above and shared with the community as the inputs to the challenges we need to solve together.

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