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to deliver the transition to a low carbon future

Study Committee B3 – Gas-Insulated Substations

Investigating contribution pathways towards Global Net-Zero using Life Cycle Assessment

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SUMMARY

As visible on the European Union (EU) website about Climate Action, *EU aims to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions. This objective is at the heart of the European Green Deal and in line with the EU's commitment to global climate action under the Paris Agreement.* Such an ambitious target includes everyone in EU, especially public and private companies among with Transmission system operators (TSOs). Several of them are already addressing ambitious targets to their suppliers to build the path toward a successful transition to net-zero.

Original equipment manufacturers (OEM) are already proposing solutions to decrease the carbon footprint of their high-voltage (HV) products with the removal of SF_6, the worst greenhouse gas ever. Even if this very important first step is mandatory to reduce carbon footprint, an important part of the carbon footprint also comes from manufacturing phase and use phase of the products. It is especially linked to metals refining and shaping processes, as well as Joule losses in primary and secondary circuits. Removing SF_6 contributes but cannot achieve, alone, sufficient impact reductions on manufacturing and use phases to reach net-zero.

This paper will focus on a 145kV GIS product whose SF_6 was already removed. Installed on current ENTSO-E grid, it appears that the main contributor are now Joule Losses (46%) and aluminium parts (41%). Four solutions are discussed in the paper to quantify how to decrease the impact of aluminium parts: use strong dielectric gas to avoid mass increase, modify the supply chain towards lower carbon content countries, include secondary aluminium and use steel instead of aluminium. It could end with a reduction of the total carbon footprint of the product by 5% to 25%.

Huge economical, technical and life cycle assessment (LCA) are now to be done to strengthen the hypothesis and deliver an economically viable solution decreasing carbon content. A key point is also to consider the full substation for the LCA, as an optimum solution for the 145kV GIS product like steel might generate drawbacks from a complete substation point of view due to huge increase of mass.

KEYWORD

Net-zero, Carbon footprint, Life Cycle Assessment, Recycled Metals

1 Introduction

Aiming to make Europe the first climate neutral continent by 2050, the European Commission has launched the EU Green Deal to support countries and industries toward a resource efficient and competitive economy. The Plan's ambitious targets include public and private sector amongst Transmission System Operators (TSOs). Particularly, certain Original Equipment Manufacturers (OEM) are addressing goals internally and externally for stakeholders to contribute to the global net-zero target.

To decrease the carbon footprint of their high-voltage (HV) products, OEM search solutions to remove SF_6, a greenhouse gas (GHG) with substantial environmental negative impact. However, as presented by Perret *et al.* (2023) [1], sufficient negative impact reductions on manufacturing and use phases to reach net-zero cannot be achieved with SF_6 removal alone. The authors state that potential levers to keep reducing the carbon content of a typical GIS product are (i) using a strong dielectric gas such as g^3, (ii) aluminium supply chain alternatives, and (iii) integrating recycled aluminium into the product.

This paper focuses on further potential carbon footprint reduction of a 145kV GIS product by implementing steel and PET as alternatives to aluminium and epoxy respectively. Thus, initially the carbon content of steel and ways to reduce it by inserting recycled steel will be investigated, followed by a comparison of aluminium and steel climate change impact. Finally, the carbon content of epoxy and alternatively using PET will be studied. To finish, a summary presenting the potential carbon reduction of a typical GIS will be described.

2 Typical carbon-footprint of a 145kV GIS

2.1 Scope of the study and Methodology

A typical 145kV Gas-Insulated Substation (GIS), [1] was taken as reference. This GIS exists in two versions, one using SF_6 and one using g^3, a C4-FN / O_2 / CO_2 gas mixture.

Figure 1 - 145kV 40kA GIS considered in the study (left: SF_6 version; right: C4-FN mixture version)

It was proven through a Life Cycle Assessment from cradle-to-grave that the GIS C4-FN mixture version drastically reduces the equipment carbon footprint [1]. In this paper, all evaluations were performed using ecoinvent version 3.8 database, cut-off system model, and IPCC 2021 method, as implemented in Simapro 9.4 calculation software. GWP is calculated on a hundred-years baseline. Focus is made on climate change impact, i.e., CO_2-equivalents and use phase is considered on ENTSO-E grid, at 372g CO_2e/kWh.

2.2 Carbon-footprint of SF_6 and C4-FN mixture solutions

It was shown that the removal of SF_6 impacts several sub-assemblies: circuit breaker is slightly bigger, sealings are changed and minor design improvements are necessary like adaptation of fast-earthing switches to switch induced currents [1]. From calculations done on SF_6 version, leaks are responsible for 36% of the total carbon footprint of the apparatus. The second contributor are Joule losses (31%) and the third one is aluminium parts (26%). The remaining parts or phases represents only 7% of the total as presented in Figure 2.

Figure 2 - Carbon origins for a 145kV SF_6 GIS (+50% vs C4-FN mixture version)

When SF_6 is removed from the apparatus, SF_6 leaks are replaced by C4-FN leaks whose GWP is not null. The reduction of the carbon footprint is still 33% which is a great step. Moreover, the repartition of the carbon footprint is widely modified. The gas is now a minor contributor while Joule Losses represents 46% of the total, aluminium parts represent 41% and C4-FN leaks only 3% as shown in Figure 3.

Figure 3 - Carbon origins for a 145kV C4-FN mixture GIS (-33% vs SF_6 version)

Aluminium impact is located during the manufacturing phase. Having a closer look on this phase, the main contributors are shown on Figure 4. After aluminium, whose impact is capital, two other materials can be highlighted: steel and epoxy, who are the second and the third contributors.

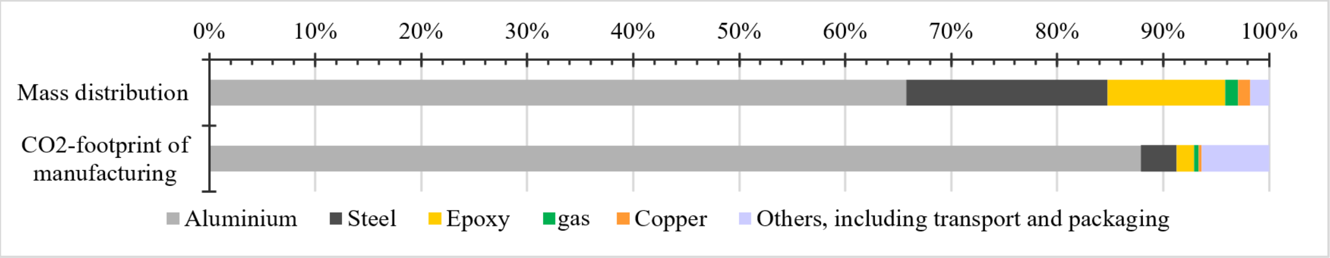

Figure 4 - Mass vs carbon footprint distributions for a 145kV C4-FN mixture GIS. [1]

2.3 Levers to reduce carbon-footprint of a 145kV C4-FN mixture GIS

The two main levers to reduce the carbon footprint are, as per Figure 3: Joule Losses and aluminium parts, which are responsible for 87% of the total carbon amount.

Joule Losses are from three categories:

- Main circuit: in this area, the design complies with IEC standard and its maximum allowed temperature near contacts and connections. An optimum between increase of aluminium mass and lower losses could be done. Impacts would depend on the electricity mix of each area.
- Instrument transformers: mainly from conventional instrument transformers using a magnetic core. Environmental relevance of shifting to LPIT (Low Power Instrument Transformer) solutions must be evaluated from a lifecycle perspective due to a different Critical Raw Materials composition.
- Mechanical drives and low voltage control cubicles: mostly coming from the anti-fogging heaters where there are substantial improvement opportunities. Solutions would require higher costs for the drives while reducing the operating expenditure for the user thanks to power consumption reduction.

About manufacturing phase, the three components to analyze are:

- Aluminium: undoubtedly became the main contributor to carbon footprint far before C4-FN losses. It represents 87% of the manufacturing impact and must be addressed to further reduce carbon content.
- Steel: with a contribution of 3.3%. It must be studied as it could be a solution to reduce the carbon content if aluminium is replaced by steel in some areas.
- Epoxy: with 1.5% of the carbon content. It is interesting to study this material in a circularity improvement approach, as it is today not recyclable, however, recyclable solutions could become a request soon.

Next chapters will address manufacturing stage with proposals for aluminium, steel, and epoxy.

3 Decrease carbon-content of Aluminium

Aluminium Green House Gases (GHG) emissions come from two main origins : the energy used for transformation and gases released during the chemical reactions [1]. Soderberg and Prebake processes also directly emits perfluorocarbons into the atmosphere, CF_4 and C_2F_6 [2]. Its production is energy intensive, therefore, manufacturing location is especially important due to local electricity mix. However, biggest suppliers are located in countries with high CO_2 energy mix (China, India, Australia) [3] with notable exception for aluminium manufacturers located in Norway and Iceland [4], having low CO_2 energy supply. The authors carried out three studies (1) decreasing aluminium mass, (2) changing the supply chain, and (3) integrating recycled aluminium.

Results show that key drivers to define aluminium mass are dielectric properties of the insulating gas for parts under pressure and the nominal current of the apparatus for parts carrying the current. Thus, a strong dielectric gas such as C4-FN mixture would allow an optimal reduction of the pressure and/or distance between active parts and earth. However, this solution is already industrialized, and no strong reduction of mass is expected in this area.

3.1 Study 1: Change Supply Chain

For supply chain changes, the authors performed nine scenarios analysis considering different countries for aluminium production, casting & milling, and assembly. The analyzed process is presented in Figure 5.

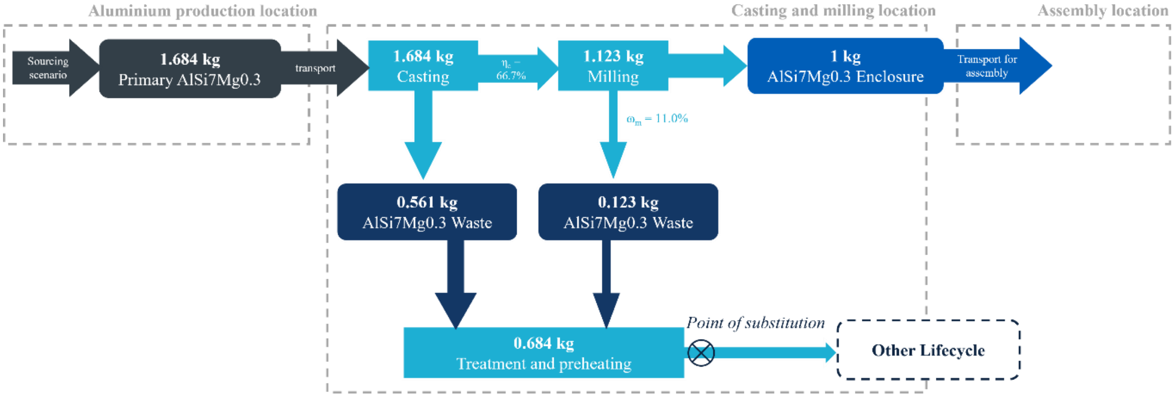

Figure 5 - Simplified representation of material flows for aluminium casted enclosures 100% primary material content [1]

Results of the nine scenarios are represented in Figure 6, below.

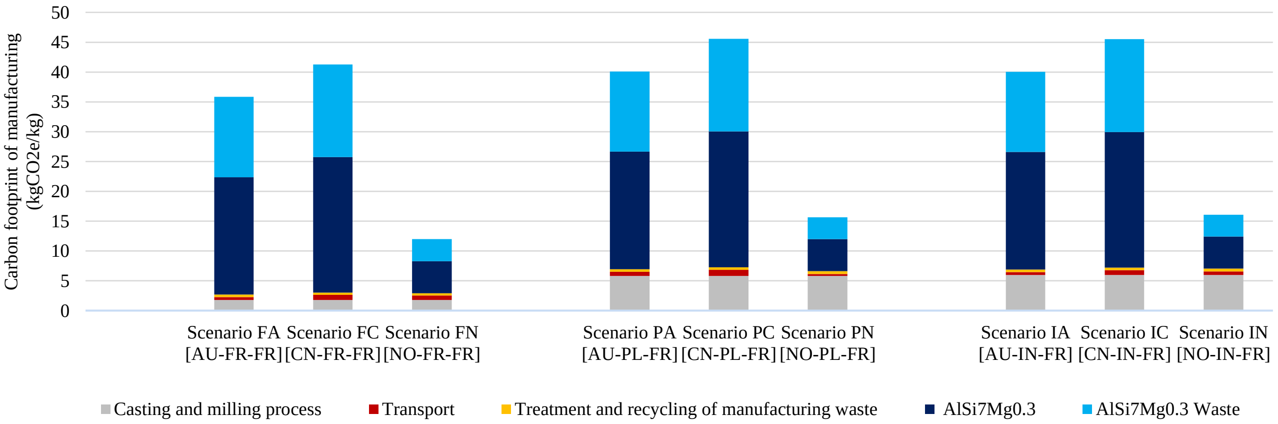

Figure 6 - CO2-footprint of 1kg of casted aluminium part depending on the sourcing scenario, grouped by casting location. [AU]: Australia, [CN]: China, [FR]: France, [IN]: India, [NO]: Norway, [PL]: Poland. First country is aluminium producer, second is the casting facility, third is the assembling factory.

The authors argue that supply chain selection to manufacture casted aluminium parts can reduce their carbon footprint and is a solution to be further investigated. However, the capacity to meet demand and economic impact of re-sourcing aluminium to Norway, which presents the best-case scenario, were not explored.

3.2 Study 2: Integration of recycled aluminium

The use of recycled content in the aluminium enclosure was studied through different hypothesis: isomass and mass increase in a ratio of 1% per each 1% of recycled aluminium content [1]. Calculations were performed assuming one casting facility based in Poland and the most divergent scenarios as presented in Figure 6, material yield (η_c) of casting was set at 66.7%. Milled value is fixed for all scenarios and it is not proportional to final part's mass. Results are shown below.

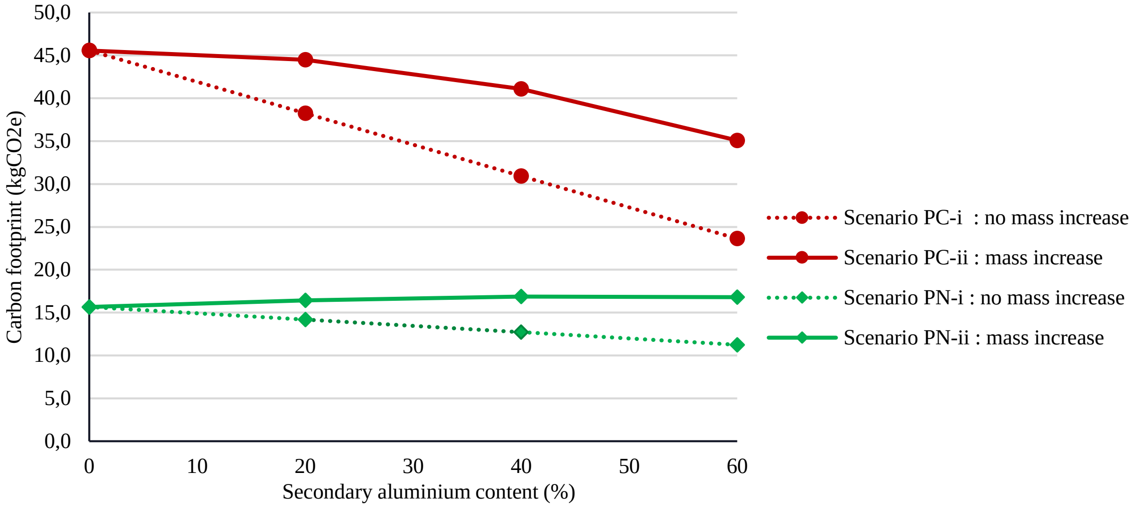

Figure 7 - CO_2-emissions per kg of casted and machined aluminium enclosures for 4 different scenarios.

The benefit from using recycled aluminium is much affected by the metal source. Hence, if raw aluminium is sourced in a carbon intensive electricity mix location, then the interest of incorporating recycled aluminium increases. Furthermore, using recycled aluminium can be a challenge since conservation of required mechanical and electrical properties and the implementation of regular verifications relative to alloy's quality would be necessary [5].

4 Decrease carbon-content of steel

The steel and iron industries are highly strategic for the European Union, counting with 2.5 million workforces including 308,000 direct jobs. However, iron and steel sector have the highest total carbon emissions compared to other energy-intensive industries. For instance, it is responsible for about 5% of CO_2 emissions in the EU and 7% globally. Hence, the development of low-CO_2 technologies for steel production is critical to respect climate targets [6].

4.1 CO_2 emissions from steel production & manufacturing

The emissions from steel production and manufacturing process are inherent to the selected technology. The most common technique is the use of coke and coal in blast furnaces in which iron ore is smelted to produce hot metal at temperatures up to 2,300°C and CO_2 due to coke combustion. Molten iron is then refined into steel, usually in a "basic oxygen furnace", where blown oxygen is used to reduce the carbon content. This primary steelmaking Blast Furnace – Basic Oxygen Furnace (BF-BOF) - emits CO_2, however, the major environmental negative contribution is due to the intense energy input needed into the process [6] [7].

The second method is smelt recycled steel scrap in an Electric Arc Furnace (EAF) to produce liquid steel. The main energy need of this process is electricity, but natural gas can also represent an energy input. Figure 8 presents the above-mentioned processes.

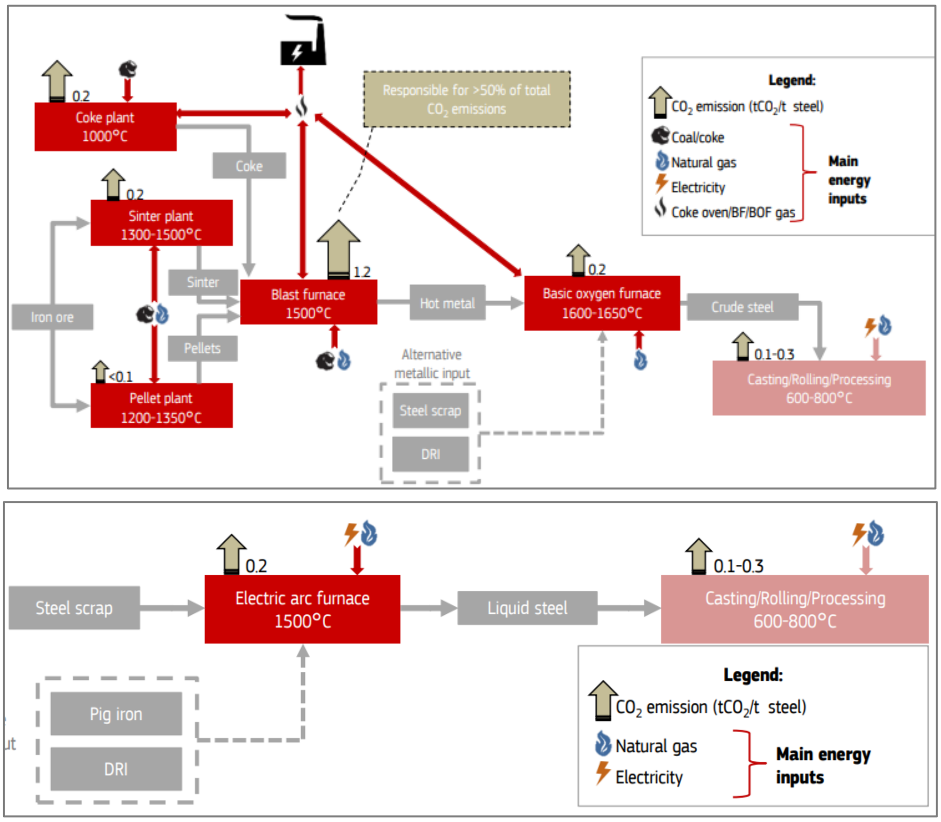

Figure 8 - Simplified flow diagrams and CO2 emissions of BO-BOF (left) and EAF (right) routes. Source: [6]

Even if the primary and secondary steelmaking routes are energy-intensive industrial processes, they can have different CO_2 emission intensities. In the BF-BOF process, carbon is not only an energy input, but it is also required to bind and remove oxygen from iron ore.

The secondary steelmaking route is widely electrified. Considering the EU electric mix CO_2 intensity, the total emissions from electrical arc furnace steel melting are vary from 0.2 to 0.3 tCO_2/t of steel: this amount only includes the iron scrap and the furnace and does not comprise additional elements that could be added to purify the scrap.

To remove carbon from steel production, the EU steel industry is mainly focusing on hydrogen-based steelmaking. This process includes the use of hydrogen to reduce iron ore to iron avoiding the use of fossil fuels. Nevertheless, the large amount of hydrogen needed is a challenge. Nowadays, 96% of hydrogen is produced by reforming natural gas, a fossil resource. In the coming years, the concern is to use sustainable hydrogen, generated by the electrolysis of water using renewable electricity. However, the cost of this production method is currently more expensive than reforming natural gas [7]: if this process fully relies on hydrogen produced thanks to direct renewable electricity, those remaining emissions are in the order of 30-250 $kgCO_2$/t steel, compared to 1.9 tCO_2/t steel in the BF-BOF route [6] [8]. Figure 9 shows a simplified diagram for hydrogen Direct Reduction of Iron (DRI) process.

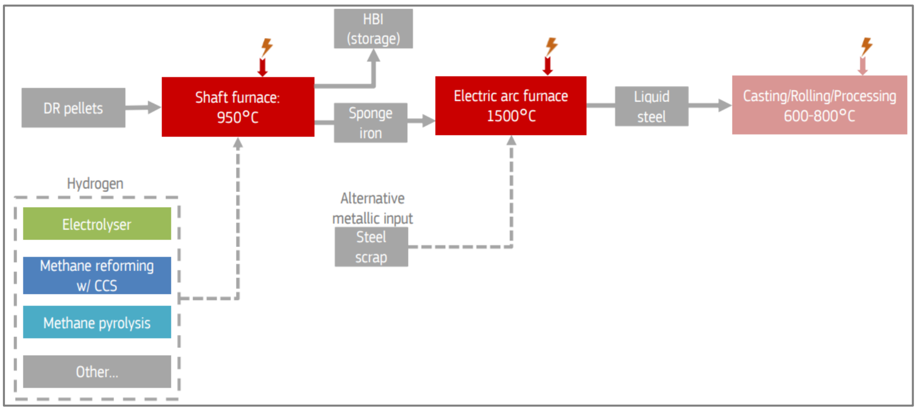

Figure 9 - Simplified flow diagram of the hydrogen DRI process. Source: [6].

Meanwhile the industry is exploring carbon capture technologies and iron ore electrolysis. Capture and storage of CO_2 have long been considered highly relevant solutions. On the production site, carbon would be captured and transported to be stored in geological formations. Another alternative technology that uses only electricity to reduce iron ore to iron is being developed. The electrolysis could reduce direct CO_2 emissions of steelmaking by 87% compared to the BF-BOF rout and the process could be near to carbon-neutrality if the used electricity is low in CO_2-emissions [6]. Nevertheless, these technologies are energy intense and require primary steel, which comes from iron mining and has a significant negative impact on the environment. Additionally, technology readiness level does not allow for industrial scale yet [9]. Thus, when feasible, the use of recycled steel is preferred.

4.2 Study 3: Integration of recycled Steel

The literature provides insights regarding steel production GHG emissions. However, as presented in section 4.1, steel carbon footprint is highly dependent on the technology and electricity mix implemented. Hence, the use of recycled steel content in the manufacturing chain was investigated through Life Cycle Assessment, from cradle to gate, both for Europe (RER) and Rest of the World (RoW) geographic locations. Modelisation was performed according to the same methodology as described in section 2.1.

It is important to mention that alloy quality variation is inherent to the use of recycled steel. Depending on the dismantling processing technology used at the End-of-life, steel scraps might contain impurities and hazardous elements. Mass changes might be required to maintain product quality standard. Hereafter, 1kg of steel was analyzed containing from 0 to 80% of secondary content. Mass changes, quality variability and potential design changes were not considered. Table 1 presents the dataset implemented for the steel environmental assessment. For the converter (primary content) iron scrap was set at zero and mass-balanced into pig iron. For the electric furnace (secondary content) the opposite was done to model recycled content. To obtain required quality steel for this application, alloying elements (Mn, Cr, Ni, Si...) have been added.

Table 1 - Dataset for steel recycling assessment performance.

Scenario	**Dataset**
RoW	Steel, low-alloyed {RoW}| steel production, converter, low-alloyed Steel, low-alloyed {RoW}| steel production, electric, low-alloyed
RER	Steel, low-alloyed {RER}| steel production, converter, low-alloyed Steel, low-alloyed {Europe without Switzerland and Austria} | steel production, electric, low-alloyed

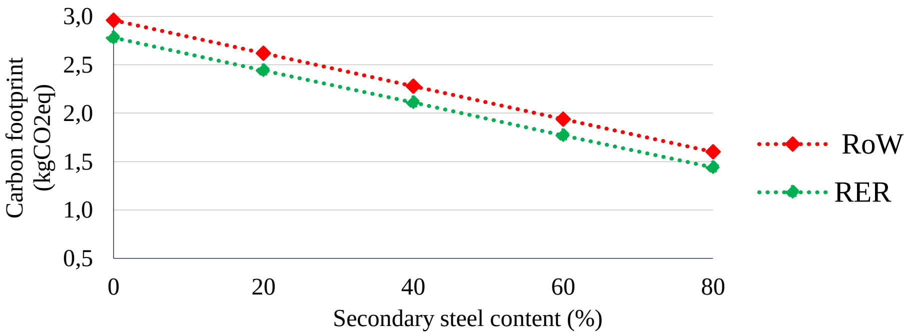

Figure 10 - 1kg steel manufacturing carbon footprint, according to secondary material content RoW/RER.

Overall, RER steel production is lower in CO_2 emissions compared to RoW specially because of a cleaner electrical mix compared to RoW. The results are different from the amount mentioned in the section 4.1 since, in the reviewed literature, only furnaces and their energy needed are considered. Thus, such difference is driven by the remaining processes as: alloying elements, quicklime, sorting and pressing of iron scrap, transportations.

4.3 Study 4: Replace Aluminium by Steel

To lower HV-equipment carbon footprint, further alternatives to primary aluminium such as steel can be investigated. Some OEM do implement steel enclosures [10].

To analyze whether this possibility would be relevant to reduce equipment's environmental impact over its lifecycle, the enclosures of a typical 145kV SF_6-free GIS have been studied [1]. A cradle-to-gate investigation was performed considering casting and milling step in Poland (similarly to aluminium in section 3.2) as displayed in Figure 11. The assembly step is not considered hereafter, as per section 3.1.

A steel enclosure is mainly conceived through wrought steel and welding. However, to achieve complex design and volume optimization, the manufacturing route for casted steel enclosure design was selected for the investigation. The value chain considered is composed of blank's casting, milling of functional surfaces, welding of accessories mount areas, coating of enclosure's interior to prevent steel oxidizing, waste preheating for reuse in the casting facility and finally shipping to the assembling factory. Baseline efficiency of casting process is set similar as per aluminium as it is highly dependent on part's geometry [1]. Milling needs are higher due to preparation for welding and chips generation rate is set as $15\%_w$ compared to $11\%_w$ for aluminium castings.

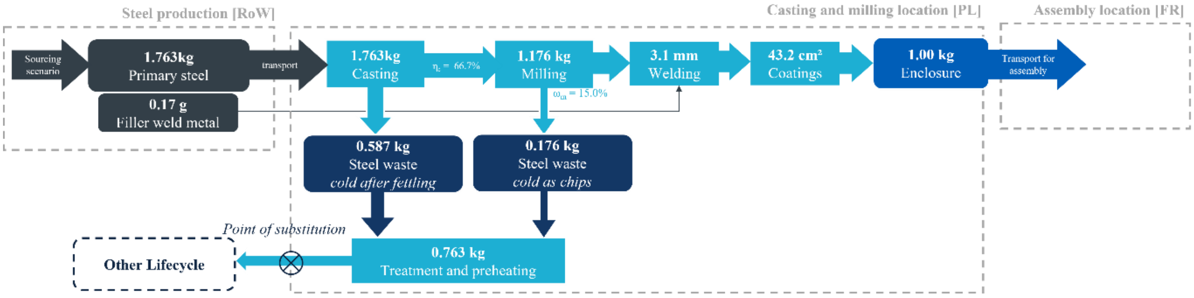

Figure 11 - Simplified flowchart of materials and processes for BF-BOF steel casted enclosures.

As demonstrated in literature, the efficiency of casting can vary depending on numerous factors among them the used technology and process. Thus, a sensitivity analysis was carried out according to what was proposed in [11] [12]. Authors state that the steel casting process has 76% and 52.2% of efficiency respectively. Datasets and Life Cycle Inventory (LCI) used for modelling are presented in Table 2.

Table 2 - LCI for steel casted enclosure sensitivity analysis.

Process	**Dataset**	**LCI** $\eta_c = 66.7\%$	**LCI** $\eta_c = 52.2\%$	**LCI** $\eta_c = 76\%$
Primary Steel alloy	Steel, low-alloyed {RoW}| steel production, converter + *alloying as in ecoinvent 3.8 database*	1.763 kg	2.253 kg	1.547 kg
Casting	Casting, brass {RER}| processing *energy adapted to steel casting and [PL] mix* [13] [14]	1.763 kg	2.253 kg	1.547 kg
Milling	Steel removed by milling, large parts {RER}| market for *no material input, adapted for [PL] mix*	0.176 kg		
Welding	Welding, gas, steel {RER}| market for* Welding, arc, steel {RER}| market for*	3.1 mm		
Coatings	Epoxy resin, liquid {RoW}| market for epoxy resin, liquid* Phthalic anhydride {GLO}| market for * Powder coat, steel {RER}| powder coating, steel	320 µm - 43.2cm² 80 µm - 43.2cm²		
Treatment and preheating	Steel, low-alloyed {Europe without Switzerland and Austria}| steel production, electric, low-alloyed *no material input, energy adapted to steel preheating only* [14] *and [PL] mix*	0.763kg	1.253 kg	0.547kg
Transport for assembly	Transport, freight, lorry >32 metric ton, euro6 {RER}	3 500 kg.km		

* *Process is allocated at 50% of the LCI value*

The carbon footprint assessment, for steel and aluminium at baseline efficiency, is presented in Figure 12. The results are shown with uncertainty bars, compared to aluminium, for 1kg of steel enclosure and projection to a full bay in an isovolumetric perspective. The uncertainty represents the efficiency variation of steel casting process.

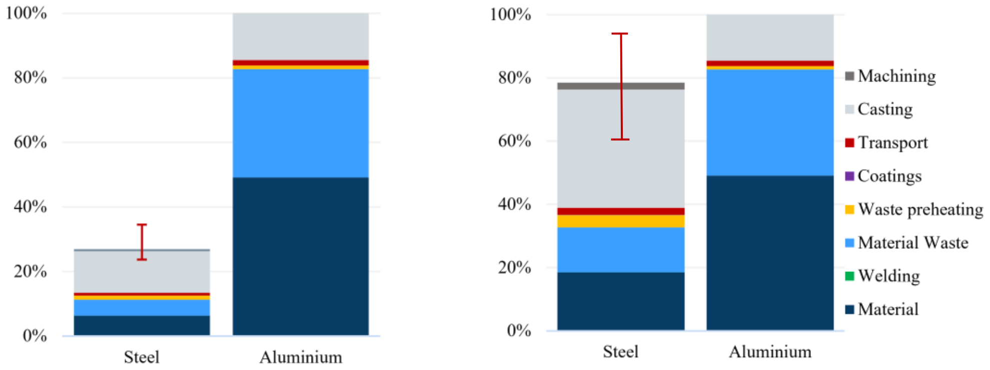

Figure 12 - Carbon footprint of manufacturing, for one kg of enclosure (left) and carbon footprint of manufacturing, full bay castings, isovolume (right).

As expected, one kg of steel enclosure is much less carbon intensive than one kg of aluminium. However, such simplification of comparing one-to-one should not be taken individually, correct evaluation is to be read Figure 12 when upscaling to a full bay is performed. Both results are much closer and vary from no significant improvement up to 31% percent carbon reduction. This levelling of benefits is due to steel higher density (7.85 kg/L compared to 2.7kg/L for aluminium). In regard of this quantification, using steel casting manufacturing route for decarbonizing will necessarily require very efficient and low-waste processes.

Greater mechanical resistance range for steels implies the need to confront the isovolumetric consideration between both solutions. If non isovolumic design is achieved thanks to enhanced material properties, then a reduction of the used mass and all related materials and energy flows, is to be expected. Forecasted carbon footprint has been computed according to the same methodology and is represented on Figure 13.

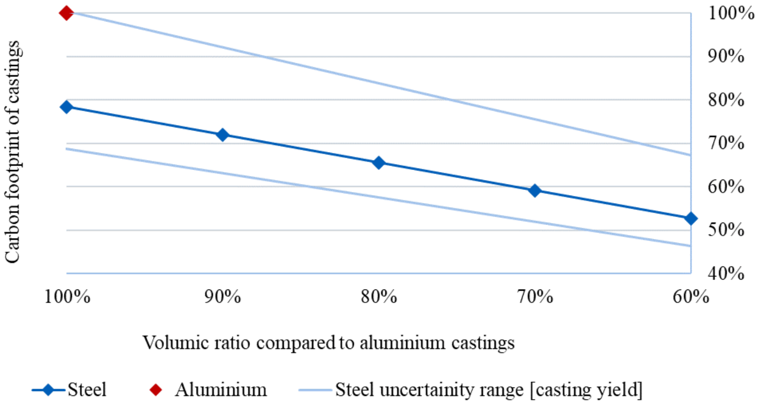

Figure 13 - Carbon footprint of hypothetical GIS steel castings depending on volume reduction

Finally, a conclusion would be that the great benefit of using steel is related to its enhanced mechanical strength allowing for further volume optimization (*high confidence*). Such design change guaranteeing a reduction of carbon footprint from a cradle to gate perspective.

5 Epoxy alternatives

5.1 CO_2 emissions from epoxy production & manufacturing

After aluminium (66%$_w$) and steel (18%$_w$), epoxy is the third most massive material (Figure 4). Despite its relatively low impact compared to the total carbon footprint of manufacturing (around 1.5%), it is ranked at the third place behind aluminium and steel [1]. Thus, it may be interesting to develop innovative ways to substitute this material, especially on a circularity point of view, as it is today not recyclable.

In GIS, epoxy is mainly used in the manufacturing of isolating plate to support conductors and provide gas partitions. Epoxy is used due to several good properties like mechanical, dielectric, resistance to SF_6 decomposition products. The epoxy used for this application is an epoxy resin filled with alumina.

5.2 Study 5: use of PET

Polyethylene terephthalate (PET) has shown that its properties enable its use as insulating material in GIS. It can resist to SF_6, C4-FN and their decomposition products. PET has a lower density and a good recyclability; it is therefore a good candidate to replace epoxy [15]. PET selected for this study is virgin PET, including losses of materials due to the creation of co-products during polymerization process. Major drawback for PET is its glass transition temperature which is much smaller than epoxy one. It requires an improved thermal design or a reduction of the nominal current of the apparatus.

To compute the environmental impact of both materials, an environmental analysis is realized based on primary data for parts' designs. For this analysis, PET plate is made by moulding, then follows a machining process while epoxy is only molded. Considered value chain and datasets are presented in Table 3.

Table 3 - Elements considered for the environmental study

	PET	**EPOXY**
Weight (kg)	0.807	1
Material	Polyethylene terephthalate, granulate {RER}	Phthalic anhydride, Bisphenol A powder, Methanol: {GLO} Aluminium oxide, non-metallurgical: {RoW}
Manufacturing Process	Injection moulding {GLO} *adapted from:* Steel removed by turning, average, computer numerical controlled {RER} [16] [17]	Injection moulding {GLO} /
Losses (%)	18.9	5.5
Waste transport	Transport, freight, lorry 16-32 metric ton, euro6 {RER}	Transport, freight, lorry 16-32 metric ton, euro6 {RER}
Waste disposal	Waste plastic, mixture {CH} sanitary landfill	Waste plastic, mixture {CH} sanitary landfill

Methodology and tools used to compare the environmental impact are identical to section 2.1. The results are given segregated by process, listed in the following Table 4 and Table 5.

Table 4 - Environmental impact on climate change of epoxy insulating plate

Impact category	**Unit**	**Epoxy resin**	**Moulding**	**Waste transport**	**Waste disposal**	**Transport to assembly**	**Epoxy waste**	**Total**
Climate Change	kg CO2-eq	2.32	1.32	0.01	0.01	0.57	0.14	**4.36**
Percentage	%	53%	30%	0.2%	0.1%	13%	3%	**100%**

Table 5 - Environmental impact on climate change of PET insulating plate

Impact category	**Unit**	**PET**	**Machining**	**Moulding**	**Waste transport**	**Waste disposal**	**Transport to assembly**	**PET waste**	**Total**
Climate Change	kg CO2-eq	2.36	0.24	1.24	0.03	0.02	0.46	0.55	**4.89**
Percentage	%	48%	5%	25%	1%	0.4%	9%	11%	**100%**

Based on our assumptions, epoxy insulating plate is less impacting on the climate change by 10.8%. Only considering materials, the impact of epoxy is close to the one of PET. However, there are real uncertainties on manufacturing processes dataset regarding generation of scrap and the energy used, injection moulding being the closest dataset available under ecoinvent. The energy used to mold PET is the same as the one chosen for epoxy while PET needs to be heated at higher temperature than epoxy as it is a thermoplastic. On the contrary, the positive impact of PET due to its recyclability was not considered while it is the major positive impact for the use of PET instead of epoxy.

Considering close results, arbitration could be made upon other indicators. PET is more impacting on ozone depletion, eutrophication, or ionizing radiation. These impacts are mainly due to terephthalic acid, and the energy used during the PET machining process. On the other hand, epoxy presents less favorable results on toxicity indicators.

The main results to have in mind is that PET, while allowing recyclability, will not help to reduce carbon content of the product. It will increase carbon emissions during production phase and there is a transfer of impact on other indicators. The uncertainties are however too high, and complementary studies are needed in the future.

6 Potential carbon-content reduction: a summary

Working on raw materials from the manufacturing phase and based on results from this paper, we can propose some scenarios to go to a carbon reduction of the aluminium parts of the 145kV GIS product. This is for indication only as there is still technical and economical clear uncertainties.

For conductors, we only consider the use of low carbon secondary aluminium with 30% of used aluminium, no mass increase. Following hypothesis are considered for enclosures:

1. Go to secondary aluminium with 30% of used aluminium, no mass increase
2. Go to secondary steel with 50% of used steel, 70% volume ratio steel vs aluminium
3. Go to low carbon secondary aluminium with 30% of used aluminium, no mass increase

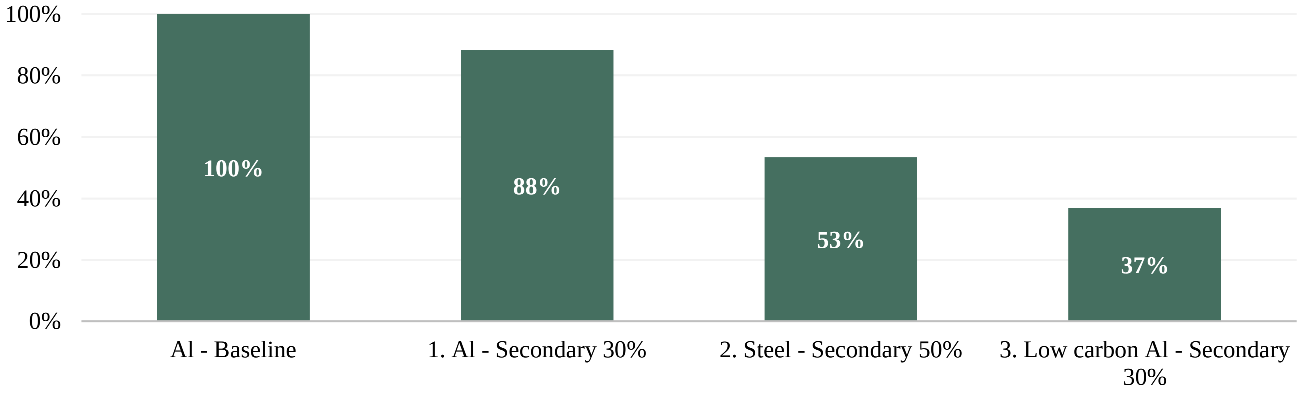

Figure 14 - Carbon content of parts in aluminium vs Low-carbon secondary aluminium for internal conductors and three scenarios for enclosures (1) (2) (3)

To go for low-carbon content aluminium is the best solutions even though economical and supply impacts must be assessed. To use steel is also a solution with major drawbacks from Joule losses in steel enclosures still to assess as well as lack of adaptability for connections of accessories on the enclosures.

The impact of huge mass increase is another drawback as it will have an impact on civil work not assessed in this study. Just like best GWP gas are not the best to optimize carbon content of a GIS, lowest carbon content using steel may not lead to an optimized carbon content of the substation [1].

7 Conclusions

A massive reduction of the HV equipment's carbon-footprint is achieved by removing SF_6 and this should remain the absolute priority, especially for high voltages and GIS where the SF_6 installed mass is the biggest.

For the future, it appears that the two main contributors to carbon footprint are now the Joule losses from the use phase and the manufacturing of aluminium parts due to strong CO_2 emission during manufacturing process. The use of a strong dielectric gas such as C4-FN mixture is key to avoid an uncontrolled rise of aluminium needs and associated perfluorocarbons emissions into the atmosphere [2].

Three solutions are proposed to reduce the impact of aluminium: modify the supply chain of aluminium, introduce recycled aluminium in most of the parts and replace aluminium by steel for enclosures.

Three scenarios are proposed to quantify potential carbon content decrease. Best solutions look to be the use of low carbon content secondary aluminium for current parts with a possibility to reduce by 63% the carbon footprint of aluminium which means 25% on total carbon footprint of the 145kV SF_6-Free GIS. The second-best option could be the use of secondary steel for the enclosure with a reduction of 47% of carbon footprint for current aluminium parts meaning 19% reduction for the full product.

However, for every solution, strong commercial and technical studies must be launched. It may be impossible to provide enough low carbon content aluminium and it could be technically irrelevant to introduce recycled aluminium for parts with strong mechanical or thermal stresses. Moreover, to introduce steel could be a better solution for carbon content of the 145kV GIS while improve the total carbon footprint of the substations due to the huge increase of mass.

Another learning comes from the proposal to replace epoxy resins by PET in order to use recyclable materials: the uncertainty is too high today to give any direction on carbon content especially considering the substitution point that is still a question to address. Keep combining economical, technical and life cycle assessment studies is mandatory to provide the best economically improved solution for environment.

8 Bibliography

[1] M. Perret, M. Chomel, S. F. Vantil, C. Dumoulin, C. Cocchi and T. Berteloot, "Remaining levers to reduce the climate change impact of today's SF6-free high-voltage equipment," in *Symposium Advanced Technologies in Electrical System (SATES),* Arras, France, 2023.

[2] I. A. Institute, "Perfluorocarbon (PFC) Emissions," 9 august 2022. [Online]. Available: https://international-aluminium.org/statistics/perfluorocarbon-pfc-emissions/.

[3] Harbor Aluminum, "Aluminum Production by Country," [Online]. Available: https://www.harboraluminum.com/en/top-aluminum-producing-countries. [Accessed 13 February 2023].

[4] IEA (International Energy Agency), "Global Energy Review: CO2 Emissions in 2021," March 2022. [Online]. Available: https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2. [Accessed 13 February 2023].

[5] J. Kasińska, D. Bolibruchová and M. Matejka, "The Influence of Remelting on the Properties of AlSi9Cu3 Alloy with Higher Iron Content," *Materials,* 2020.

[6] JRC (Joint Research Centre), "Technologies to decarbonise the EU steel industry," 2022. [Online]. Available: https://publications.jrc.ec.europa.eu/repository/handle/JRC127468.

[7] A.Bhaskar, "Decarbonizing primary steel production : Techno-economic assessment of a hydrogen based green steel production plant in Norway," 2022.

[8] J.-P. Birat, F. Patisson and O. Mirgaux, "Hydrogen steelmaking, part 2: competition with other net-zero steelmaking solutions–geopolitical issues," *Matériaux & Techniques,* 2021.

[9] "BBC," 2023. [Online]. Available: https://www.bbc.com/news/business-64538296.

[10] E. C. f. Standardization, *EN50068:2018 HV Switchgear and Controlgear – Gas-filled wrought steel enclosures,* 2018.

[11] K. Salonitis, M. Jolly, E. Pagone and M. Papanikolaou, "Life-Cycle and Energy Assessment of Automotive Component Manufacturing: The Dilemma Between Aluminum and Cast Iron," *Energies,* vol. 12, p. 23, 2019.

[12] J. M. Cullen, J. M. Allwood and M. D. Bambach, *Mapping the global flow of steel: from steelmaking to end-use goods,* Cambridge, United Kingdom: Department of Engineering, University of Cambridge, 2012.

[13] Monroe, "Energy Efficiency in steel casting production," 2008.

[14] EC-JRC, "Best Available techniques Reference Document for the smitheries and Foundries Industry - Draft 1," 2022.

[15] Petcore, "Recycletheone," [Online]. Available: https://www.recycletheone.com/fr-FR/quest-ce-que-le-pet.

[16] J. &. B. C. &. B. S. &. I. M. Faludi, "Comparing Environmental Impacts of Additive Manufacturing vs. Traditional Machining via Life-Cycle Assessment.," *Rapid Prototyping Journal.,* 2015.

[17] A. B. Jdidia., *Nouvelle méthode de génération de gammes de fabrication prenant en compte des paramètres économiques et environnementaux. Génie mécanique [physics.class-ph].,* Université Paris-Saclay; Université de Sfax (Tunisie), 2019.