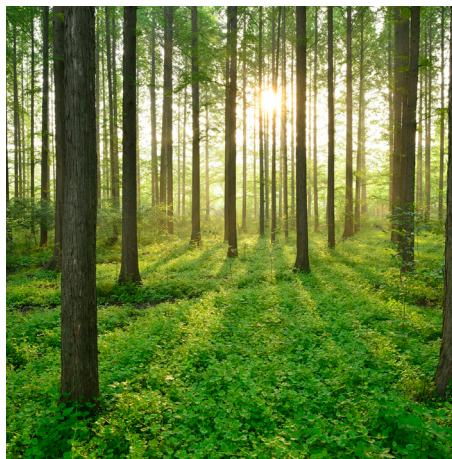
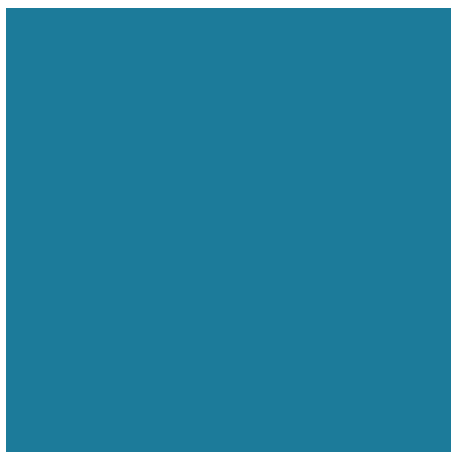


# REPLACEMENT OF SULFUR HEXAFLUORIDE (SF<sub>6</sub>) EQUIPMENT IN THE POWER SYSTEM

REPORT 2025:1085



UNDERHÅLL AV ELNÄT





# **Replacement of sulphur hexafluoride (SF<sub>6</sub>) equipment in the power system**

An economical and environmental sustainable approach

GUILLERMO MORAL OTEGUI

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## Förord

**Programmet *Underhåll av elnät* har initierat projektet *Ersättande av SF6-komponenter i kraftsystemet*. Projektet har undersökt hur vi kan med maskininlärning detektera när nuvarande SF6-komponenter som finns i elkraftsystemet behöver bytas ut och hur bytet ska genomföras. Varianter har utvärderats med avseende på ekonomisk och miljömässig hållbarhet.**

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Följande bolag har deltagit som intressenter till projektet. Energiforsk framför ett stort tack till samtliga för värdefulla insatser

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These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

## Summary

**Sulphur hexafluoride (SF<sub>6</sub>) is a gas used as the insulator medium of high voltage equipment in substations due to its very high dielectric strength and recovery properties after an arcing fault. However, it has an extremely high Global Warming Potential, 23,500, that makes leakage from the equipment a serious environmental problem. As the current equipment reaches the end of its lifetime and more strict regulations are introduced in the EU, companies are looking into more sustainable alternatives to replace them.**

This project studied the challenges of the transition for High Voltage Gas Insulated Substations. After a review of the alternative technologies, NOVEC™ 4710(C4-fluoronitrile) mixtures and air were considered the most viable. Their environmental and economical impact was estimated in a series of simulations that project the power system from 2020 to 2050, and a posterior analysis of variance to identify statistical significance.

The results show that a progressive replacement of SF<sub>6</sub> with NOVEC™ 4710 can reduce emissions of greenhouse gases by 42.19%, whereas replacement with air only reaches 32.35% reduction. This difference was statistically significant with a p-value of 7.7e-6. More extreme replacement plans resulted in higher reductions, but the investment needed was considered unreasonable.

The biggest factor on emissions was found to be the manufacturing footprint of the device. This penalizes air-based devices because, due to their worse insulation, they are bigger in volume and mass, consuming more resources in this phase even though they do not produce emissions during operation. Thus, a progressive replacement with NOVEC™ 4710 is the recommended option from this study.

## Keywords

Electrical equipment, Gas insulated switchgear, Phase out, Sulfur hexafluoride, Substation.

## Sammanfattning

**Svavelhexafluorid (SF6) är en gas som används som isolationsmedium i högspänningsutrustning i transformatorstationer på grund av dess mycket höga dielektriska styrka och återhämtningsegenskaper efter ett ljusbågsfel. Den har dock en extremt hög global uppvärmningspotential, 23.500, vilket gör läckage från utrustningen till ett allvarligt miljöproblem. I takt med att den nuvarande utrustningen når slutet av sin livstid och strängare regler införs i EU, söker företagen efter mer hållbara alternativ för att ersätta den.**

Detta projekt studerade utmaningarna med övergången till gasisolerade transformatorstationer för högspänning. Efter en genomgång av alternativa tekniker ansågs NOVEC™ 4710 (C4-fluoronitril)-blandningar och luft vara de mest lönsamma. Deras miljömässiga och ekonomiska påverkan uppskattades i en serie simuleringar som projicerar kraftsystemet från 2020 till 2050, och en posterior variansanalys för att identifiera statistisk signifikans.

Resultaten visar att en gradvis ersättning av SF6 med NOVEC™ 4710 kan minska utsläppen av växthusgaser med 42,19%, medan ersättning med luft endast ger en minskning på 32,35%. Denna skillnad var statistiskt signifikant med ett p-värde på  $7,7 \times 10^{-6}$ . Mer extrema utbytesplaner resulterade i högre minskningar, men den investering som krävdes ansågs orimlig.

Den största faktorn för utsläppen visade sig vara tillverkningen av fotavtryck från tillverkningen. Detta missgynnar luftbaserade enheter eftersom de, på grund av sin sämre isolering, är större i volym och massa och förbrukar mer resurser i denna fas, även om de inte producerar utsläpp under drift. Därför är ett successivt utbyte mot NOVEC™ 4710 det rekommenderade alternativet i denna studie.

## Keywords

Elektrisk komponenter, Gasisolerade ställverk, Utfasning, Svavelhexafluorid, Transformatorstation

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# 1 Introduction

**This first chapter introduces the project, giving some background to better understand what problem the thesis is trying to answer and why it is necessary. The initial plan shows the project's structure, what activities must be done to achieve the results and how they are scheduled. Finally, there is a brief discussion on the methodology, giving insight and justification to the choice of methods.**

## 1.1 BACKGROUND

Sulfur hexafluoride (SF<sub>6</sub>) is a gas that has had a very important role in the power system since the 1970s thanks to its unique properties. It is a very electronegative gas with a dielectric strength 2.5 times greater than air at atmospheric pressure, which makes it a great electrical insulator. Its high thermal conductivity allows for a faster cool-off of an electrical arc, which, along with a unique fast recombination, makes it a great long-term arc quenching medium for circuit breakers. With its great stability and long lifetime, it needs low maintenance and refilling.

Because of these properties, it is widely used as an insulating medium for Gas insulated switchgear (GIS), specially in High Voltage (HV) applications, and it is practically the only medium used for Extra High Voltage (EHV) and Ultra High Voltage (UHV)–greater than 345 and 765 kV respectively.

It has helped to significantly reduce the size and weight of these devices resulting in more compact systems as it can provide high dielectric strength in less volume. For example, a 65% reduction in packing volume at 145 kV is seen between two GIS from Siemens, the model 8D2 from 1968 and the model 8DN8 from 2010 [1]

However, SF<sub>6</sub> is unfortunately the world's most potent Green House Gas (GHG) with a Global Warming Potential (GWP) 23,500 times greater than Carbon dioxide (CO<sub>2</sub>) [2]. For this reason it must be phased out of the system.

In Sweden 155 tons of SF<sub>6</sub> are installed across the one hundred and seventy five substations and switching stations in the power grid (data of 2021, [3]). 0.24 tons were leaked during operation, or 0.15% of the total amount. Including accumulated stock and other electrical equipment, the amount of SF<sub>6</sub> increases to 241 tons, and the leaks to 1.4 tons, the equivalent of 32,900 tons of CO<sub>2</sub> (data of 2019, [4]).

The European Union (EU) made a proposal to update Regulation (EU) 517/2014 on the 5th of April of 2022, that is under review at the time of this report, with a higher objective of reducing Hydrofluorocarbons (HFCs) on the market by 98% in 2050 compared to 2015 [5]. This legislation will affect SF<sub>6</sub> and makes it necessary to evaluate the current plan for its phase out of the power system.

This must be done in an efficient manner. The premature replacement of all devices with SF<sub>6</sub> has been estimated to have a cost between SEK 17-23 billion by

one of Sweden's largest electricity grid companies [Energiforsk, personal communication, June 9<sup>th</sup>, 2023]. This is not a viable investment.

It would also have negative effects in Europe's current renewable energy plan to reach emission's targets. By 2030, the EU has a target of renewable sources of 42.5% [6], specifically, for solar power the target is 750 GW, with only 208 GW currently installed [7]. This requires a rapid expansion of switchgear and network equipment. Facing this expansion with a premature replacement of SF6 could have the opposite result as the alternatives are not matured enough, the European Network of Transmission System Operators for Electricity (ENTSO-E) warns in its feedback to the EU [8].

An accelerated dismantling due to maintenance or repair cut-off dates and retroactive requirements on existing equipment will cause high costs, major bottlenecks in supply interruptions and lead to delays in the deployment of renewable energy sources. It is important to focus on promoting the introduction of new technology in new projects, while allowing existing equipment to continue to operate until the end of its useful life.

## 1.2 PROBLEM

The phase out of SF6-equipment in substations faces a series of technological and logistical challenges. The power grid is a huge infrastructure. In Sweden, simply considering the transmission level, it consists of 175 substations and switch stations across 17,500 km of power lines, and it involves 16 connections to other countries [9]. Replacing all the equipment will be a project of enormous size.

Furthermore, it presents some conflicts or anti-synergies with other sustainability factors. Regarding the environmental impact, although it will reduce the emission of SF6 during operation, it could slow down the incorporation of renewable energies, which would increase indirect CO2 emissions.

It also enters in conflict with economical sustainability, as a project of this size would incur in significant costs in an inefficient manner, diverting funds from projects that could improve other sustainability factors.

Finally, there is also a technology impediment, as many of the alternatives are not matured at the moment, specially for EHV and UHV.

In this project we look to answer the following questions:

1. How can the phase out be handled in an efficient and rational way? Do we need to replace all components directly, or can we change them in a more need-driven approach?
2. What equipment should we use instead of the one containing SF6?
3. What is most cost-effective and best from an environmental point of view for each application? 3. How can replacement need be detected? Can cheap sensor-systems do this? Can the implementation of machine learning help?

### 1.3 PURPOSE

A lot of research has been and is currently being conducted studying the alternatives for SF6. However, research has focused on the technical characteristics. The economic factor of their implementation has not been studied as much, and presents a research gap that is very important for the sustainable agenda.

The purpose of this project is to analyze all the factors that affect the phase out and, as a result, to propose an Economy and Ecology (Eco-Eco) efficient replacement plan. Furthermore, it also investigates tools to facilitate said plan, such as machine learning applications to detect the Remaining Useful Life (RUL) of the equipment, a deciding factor on when to replace old devices.

The body of work produced in the project could be used as a reference for the companies to develop their own replacement plans. This would be of great benefit, reducing planning times and promoting sustainable solutions.

The Eco-Eco approach could benefit not only companies, but the country as a whole with a more sustainable power grid. It is potentially beneficial to many of the current Sustainable Development Goals (SDGs) of the Agenda 2030. Specifically, it will have positive effect on the following goals:

- *SDG 7 Affordable and Clean Energy*, as it looks to improve the grid with clean alternatives.
- *SDG 9 Industry, Innovation and Infrastructure*, as it studies new emerging technologies in an industrial context.
- *SDG 11 Sustainable Cities and Communities*, proposing changes to renovate distribution stations located in cities.
- And it would avoid potential negative effects on *SDG 8 Economic Growth* and *SDG 13 Climate Action*, studying the impact of different implementation plans.

### 1.4 GOALS

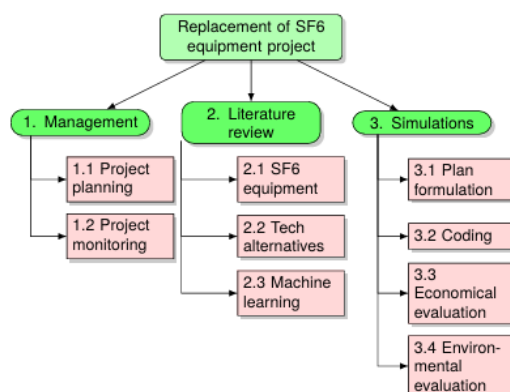
The goals of the project are to evaluate the different alternatives to the current devices from an Eco-Eco efficiency point of view and use this information to formulate a replacement plan. The thesis focuses on HV equipment, where most of the challenges lie. It is organized in the following points:

- Study and evaluate the different alternatives to SF6 equipment.
- Analyze, evaluate and compare the economical and environmental impact of different models of phase out plans.
- Study the detection of replacement need to look for a simple and affordable method.
- Propose a replacement plan.

The project results are presented in this written report with the methodology, results and conclusions.

## 1.5 PLANNING

The project went through various revisions of scope. Figure 1-1 shows the Work Breakdown Structure of the tasks in its last iteration.



**Figure 1-1 Work Breakdown Structure of the project**

The first step of the project was an extensive literature review (work package 2). It covers the background (the properties of SF6 and the devices that use it), the alternative technologies and the application of machine learning for monitoring.

Using the information on SF6 as a baseline, the alternatives were compared based on their performance, GWP, cost, Technology Readiness Level (TRL), and other unique relevant factors (e.g. whether it is toxic).

The conclusions from this comparison were then used to formulate the replacement plans in package 3.1. The plans are evaluated through the results from simulations, which have to be coded (package 3.2) in Matlab. Finally, results are studied with a statistical analysis (packages 3.3 and 3.4).

These activities and deliverables are scheduled as indicated in the Gantt diagram, Figure 1-2.

**Table 1-1 Milestone meetings schedule**

| Date                      | Point                                                  |
|---------------------------|--------------------------------------------------------|
| Monday, 11th of September | First Summary after State of Art research.             |
| Monday, 6th of November   | Midpoint of the project. Progress update.              |
| Monday, 8th of January    | Project update and evaluation to lead to proofreading. |

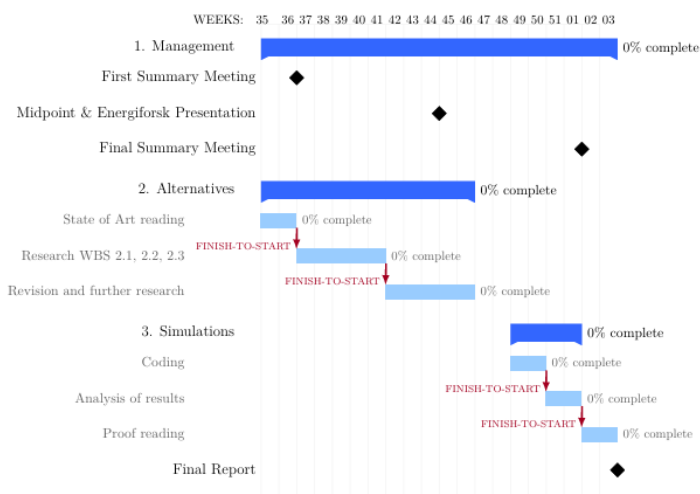


Figure 1-2 Gantt diagram of the project

## 1.6 DELIMITATIONS

The project covers the research on the alternative technologies to SF6 at HV and their implementation in an efficient way. It also explores helpful tools for this objective, such as the use of machine learning to analyze RUL, as proposed previously in the research questions and the planning.

The project does not include the development of any of these technologies nor their actual implementation, as none of these factors are under our jurisdiction.

Various risks were considered in the planning phase: lack of information on alternative technologies, lack of information on the system, and lack of access to data for machine learning. Under these risks, it was decided to change the scope as a countermeasure.

From the first two, **the scope of the simulations was limited to switchgear devices at HV**. Some assumptions had to be made, as discussed on Section 1.7. The direct application of machine learning, initially intended, was taken out, instead carrying on a literature evaluation of published methods.

## 1.7 RESEARCH METHODOLOGY

As discussed previously, the first step of the project was to research, analyze and compare the alternative technologies to SF6. This has been done through literature review of the state of the art. Their technical and environmental characteristics have been researched by multiple studies. As they are published under peer review, it is assured that they follow good praxis and valid methodology and methods.

The sources consulted have been limited to ten years prior, 2013-2023, with the exceptions of legacy works that can be important to understand the context—for example, *SF6 Switchgear* by Ryan and Jones [10].

Avoiding older publications is important for two reasons: first, from a research point of view, it helps to avoid repeating work that has already been done, which would lose time without providing new value to the project. Second, one of the challenges of the phase out is the maturity of the alternatives. Many of these are very new and are, therefore, subject to more recent developments.

Along with articles from the manufacturers that are developing the new SF6-free products, independent ones have been also included to ensure an ethical and objective approach and to avoid biases.

The environmental impact has been estimated with a LCA using the norm ISO 14040 and its application by Hitachi as reference ([11], [12]). This framework looks at the possible impacts during the whole life of a product: manufacturing, operation and decommission. It is an international norm validated by the competent organisms and widely used in the industry.

#### **Evaluation of replacement need detection and machine learning.**

The research on tools to help identified RUL (sensors, machine learning) is also done via a literature review and qualitative discussion, following the general indications given before.

Practical application faced problems discussed in the Delimitations, and thus was discarded.

#### **Evaluation of replacement plans.**

The different plans are compared through the simulation of future scenarios and the statistical analysis of the results.

More specifically, the phase out analysis consisted of projecting five plans from 2020 to 2050:

- Business as usual: SF6 is not phased out.
- The standard plan: replacement as needed, SF6 is decommissioned as the device reaches the end of its lifetime.
- The hard plan: all SF6 equipment is immediately replaced at the start, year 2020.
- The delayed plan: SF6 phase out is delayed until 2030., from when it follows the standard plan.
- The half-life plan: replacement as needed, but SF6 equipment is replaced when it reaches half its lifetime.

This approach has been used repeatedly in energy planning when evaluating the impact of renewable energies and other policies.

Bilen, Maes, Larrain and Braet made a similar study in [13], which has been used as reference. Their paper focuses only on CO2-eq emissions, and it covers the whole EU. This project will expand on the impacts, including costs, and on the

scenarios presented, while reducing the scope to only Sweden, to find results suited specifically for this country. It is also different in the technologies studied.

To make the models, official scenarios have been used: the EU reference scenario for 2050 [14] and Sweden reference scenarios by Svenska Kraftnät [15] and the Nordic grid [16].

As there exists a linear relationship between SF<sub>6</sub> stock and grid capacity [17], calculating the parameters of said relation through linear regression is a valid method that allow us to estimate SF<sub>6</sub> in the future using the expected power capacity increase in the reference scenarios.

The current stock of SF<sub>6</sub> in Sweden were obtained from the official reports of Energi Företagen [3] and the National Inventory Report for the United Nations Framework Convention on Climate Change (UNFCCC) [4]. However, this information comes from estimations made by the governments and not from strict monitoring. The impact of this estimation was evaluated through a sensitivity analysis.

Other important values such as leakage rates can be obtained from manufacturers guides and standards and have been modeled as PERT Probability Density Function (PDF) between minimum and maximum values.

Given the uncertainty of some of the values, the use of stochastic variables that encompass best and worst scenarios should reduce bias on the results for example, if only the expected leakage rate during operation was used, the results would be overly optimistic as incidents with higher rates are ignored.

Therefore, the method used was a comparison of treatments using statistical methods. An Analysis of Variance (ANOVA) determines if any of the proposed plans has a statistically significant difference with the rest. Then, the mean CO<sub>2</sub> emissions and costs of each plan are compared against the others, and the significance of the difference is determined against a Student's t-distribution. Internal validity is assured with the evaluation of the hypothesis. The proper use of these methods is very important to validate the results and to draw conclusions solidly based on a good methodology.

A sensitivity analysis was also done to identify the factors with higher impact. This consists on modifying slightly one of the parameters and looking at the change of results. It is relevant to interpret the results, as more emphasis should be put on the factors with higher effect on the phase out, but it is also a sign that the uncertainty of that parameter should be studied further, thus helping to ensure the quality. A sensitivity analysis like this one is used abundantly in research and it is considered a valid method by the scientific community.

This approach may have suffered from external validity, or whether the model of the scenarios are a good representation of the real target (the future of the Swedish system). It includes simplifications and idealizations that separate it from reality. This could affect the data it produced and invalidate its extrapolation. This has been mitigated using official sources for the scenarios and parameters, as it was discussed.

## 1.8 STRUCTURE OF THE THESIS

Chapter 2 summarizes the literature review of the state of the art and presents the relevant background information regarding SF<sub>6</sub> equipment.

Chapter 3 summarizes the literature review of the alternative technologies and makes conclusions that are then fed into the formulation of replacement plans.

Chapter 4 describes in detail the methodology and methods employed.

Chapter 5 presents the scenario and model characteristics, and the simulations done with them.

Chapters 6 show the results of the different phase-out scenarios and the statistical comparison with illustrative graphs and tables, and discuss them to answer the research questions and propose an efficient phase out plan.

Finally, Chapter 7 makes the conclusions, looking into the success of the project and how it can be improved or expanded in future work.

## 2 Background

This chapter delves in detail into the background aspects of the SF<sub>6</sub> technology in the grids. This information is the result of the research on the state of the art done at the beginning of the project and serves as a basis for the studies developed in future chapters. It is divided in three sections.

**Sulfur hexafluoride SF<sub>6</sub> Characteristics and properties** presents the form of the gas' insulation properties. This explains its importance in the previous decades and sets the bar for the alternative insulators.

**Current electrical equipment** discusses the devices installed in the substations as of today. It presents the use of SF<sub>6</sub> in each of the devices and voltage levels, to identify the more critical ones. And finally, it analyzes the characteristics of devices from Siemens and Hitachi Energy as examples, which can be use to compare with the SF<sub>6</sub>-free equipment that is being built.

Finally, **Current status in Europe** presents the current policies of the EU regarding SF<sub>6</sub>, the use and emissions of the gas both in the EU and Sweden.

### 2.1 SULFUR HEXAFLUORIDE SF<sub>6</sub>: CHARACTERISTICS AND PROPERTIES

Sulfur hexafluoride (defined with the chemical formula SF<sub>6</sub>) is an artificial inorganic compound widely used in the electric field as an insulator and breaking medium. It was first synthesized from elemental sulfur and fluorine in 1901 by the French chemists Henri Moissan and Paul Lebeau; the former won the Nobel Prize in Chemistry in 1906 for his work with this element.

The compound consists of six fluorine atoms linked with a covalent bond to a central sulfur atom, Figure 2-1. It has a low boiling point even at high pressures, as seen in Figure 2-2, so it is a gas at normal conditions (25°C, 1 atm). It has a very unique set of properties, combining both a very high dielectric strength—2.5 times higher than air at atmospheric pressure—and great arc quenching capabilities—100 times higher than air.

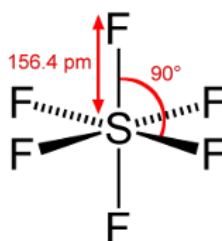


Figure 2-1 Molecule of SF<sub>6</sub>. Source: released to Public Domain

It is very stable and chemically inert, which reduces the reactions when it is exposed to the higher temperature and pressure by an electrical arc. Additionally, it has an almost complete recombination after the event. Both of these properties give it a very long lifetime in operation.

It also is non-flammable, non-explosive and non-toxic, which allows for it to be used without risks to safety. But, as other fluoride compounds, it is a greenhouse gas, contributing to climate change and global warming.

The gas has been utilized prominently in electrical engineering since the 1970s as an insulator and breaker medium on grid equipment (circuit breakers, switchgear). This is especially the case in HV, EHV and UHV, where there are less alternatives to the gas.

The use of SF<sub>6</sub> by this industry represents the 80% of the total production of the gas ([18], [19]). It has had other uses in the magnesium industry (4%), in electronics (8%), as a filler for tires or trainer shoes' soles (3%), and in a less capacity in particle accelerators, optical fiber production, lighting, medical, pharmaceutical, and soundproof windows (5%) [19]. However, its use outside of HV equipment has been limited by the EU Regulation on F-gases [5].

### 2.1.1 Pressure and temperature characteristics

In order to be a good insulator, compounds must both be in gaseous state and sealed at high pressures, which can be difficult at low temperatures (more detail in Section 2.1.2).

This is a challenge because low temperatures are usually a requirement for switchgears. If they are part of an outdoor installation, they will be subject of the low winter temperatures, which in Sweden easily reach values below 0°C. In indoor installations temperatures can be kept higher more easily, but in many cases at a high cost on heating. The International Electrotechnical Commission (IEC) in the norm 62271:2023 [20] defines -25°C and -5°C as minimum requirements for outdoor and indoor installations respectively. Many gases that have good insulation properties cannot be used because their boiling point is higher than these values.

SF<sub>6</sub> has a low boiling point of -63.8°C [21], lower than the threshold in the standard, and can operate in gaseous state at 25°C under pressures as high as 0.5 MPa. Figure 2-2 shows the Pressure/Temperature/Density characteristic of SF<sub>6</sub>, and Table 2-1 Saturated vapor pressure of SF<sub>6</sub>. Data from [21] shows the saturated vapor pressure of the gas for temperatures between -30°C and 30°C; these values are the limit for the GIS equipment in order to not liquefy the gas and reduce its insulation capabilities.

The critical temperature is high, 45.5°C [21]. Therefore, the gas can easily be liquefied at room temperatures, which is useful for storage and transport purposes, but can be a problem in its application.

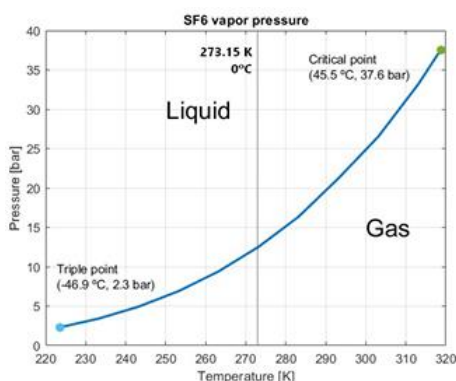


Figure 2-2 Pressure/temperature state diagram for SF6. Source: own work

Table 2-1 Saturated vapor pressure of SF6. Data from [21]

| Temperature (°C)                | -30  | -20  | -10  | 0    | 10   | 20   | 30   |
|---------------------------------|------|------|------|------|------|------|------|
| Saturated vapor pressure, (MPa) | 0.49 | 0.68 | 0.93 | 1.24 | 1.61 | 2.06 | 2.59 |

### 2.1.2 Insulation properties

SF6 is a very electronegative gas due to the presence of fluorine in the molecule, the most electronegative element with a value of 3.98 in the Pauling scale. Because of this, SF6 has a high tendency to adsorb electrons, impeding the free movement of these particles.

SF6 also has great dielectric strength, which allows it to withstand high voltage levels without suffering a breakdown. Under uniform electrical fields, it has a dielectric strength of 885 kV/(cm MPa), between 2.5 to 3 times higher than the dielectric strength of air, 294 kV/(cm MPa).

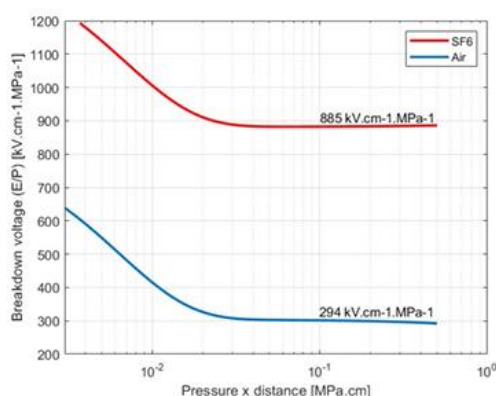


Figure 2-3 Dielectric strength under uniform electric field of air and SF6. Source: own work, data from [21]

Its breakdown voltage follows Paschen's law (Equation 2.1) up to 0.2 MPa, but starts to deviate at higher pressures. Like other gases, the breakdown voltage increases with the gas' pressure and the distance of the electrodes, as seen in Figure 2-4.

$$V_B = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{sec}}\right)\right]} \quad (2.1)$$

where  $V_B$  is the breakdown voltage,  $B$  is a factor related to excitation and ionization energies,  $p$  is pressure,  $d$  is density,  $A$  is a factor related to the saturation ionization in the gas, and  $\gamma_{sc}$  is the secondary electron emission coefficient.

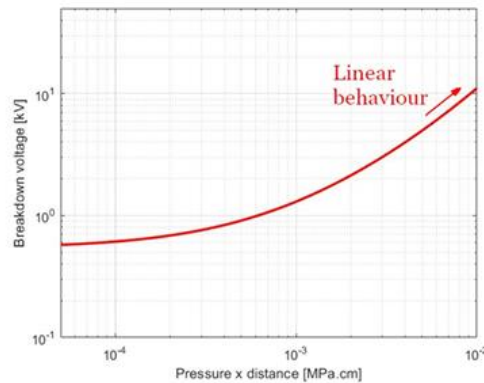


Figure 2-4 Paschen curve of SF6 under uniform electric field. Source: own work, data from [21]

This behavior explains the need for operating at high pressures in GIS. For a given breakdown voltage, operating at a higher pressure allows to reduce the distance between conductor parts, reducing equipment volume. On top of that, when comparing two gases, the one with the higher dielectric strength will be able to reduce the volume even further.

However, a gas' dielectric strength drops in the liquid state, and therefore the pressure must not be high enough to liquefy it. SF6 can withstand high pressures in gaseous form, as seen previously in the state diagram, Figure 2-2, which is an advantage against other alternatives.

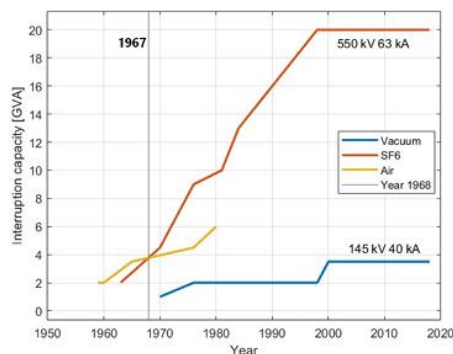
Comparing the breakdown voltage of different insulator mediums (vacuum, solid, oil, air and SF6), high pressured SF6 achieves the highest breakdown voltage with the lowest insulation distance and, therefore, the lowest equipment volume. For this reason, SF6 has dominated as an insulator medium for EHV and UHV, and in substations located in urban areas where space is a limited resource.

Furthermore, experimental tests have shown that SF6 has a flat  $V-t$  (Voltage time) characteristic ([22], [23]). The breakdown voltage has a very low dependence on exposure time, so the gas can protect the device of overvoltages for long periods of time.

### 2.1.3 Arc quenching properties

The arc breaking process is divided in three phases: the arcing period, the thermal recovery period and the dielectric recovery period. For a material to be a good arc-extinguisher it has to have good insulator capabilities, good thermal properties, and fast dielectric strength recovery.

SF6 excels at these three aspects, being able to extinguish an electric arc 100 times faster than air [22]. Current SF6 circuit breakers have reached levels of 550 kV and 63 kA (Figure 2-5), much higher than alternatives based on air or vacuum.



**Figure 2-5 Interruption capacity of different mediums. Source: own version based on [24]**

Electric arcs have an average temperature between 1,000 K and 3,000 K [21], and the core of the arc can reach higher temperatures up to 12,000 K [25]. SF<sub>6</sub> suffers decomposition in other compounds from temperatures of 2,000 K [10] [21]. The products of this reaction present higher thermal conductivity (of an order of magnitude higher than at ambient temperature [10]) and high affinity for free electrons. This leads to a fast dielectric recovery, and a fast thermal recovery (3  $\mu$ s compared to 8  $\mu$ s for air [10]).

Convection is also a very important method for heat dissipation, and it is dominant in gases. This mechanism is governed by the convection factor,  $h$ . SF<sub>6</sub> is denser than air, which contributes to having a higher convection factor and, thus, dissipating more heat through this mechanism.

SF<sub>6</sub> also presents a unique self-regeneration after the arc event. This increases its lifetime, reduces maintenance and eliminates the need to refill equipment. It is also important because some of the decomposition products are toxic and recombination eliminates them.

#### 2.1.4 Decomposition

SF<sub>6</sub> is thermally stable at temperatures below 800 K. However, when exposed to the high temperatures of electric arcs, it decomposes into other products. Initially, at temperatures between 800 K and 1,400 K, it decomposes to SF<sub>4</sub> and F, to then finally form charged ions S and F at temperatures higher than 3,000 K [21].

These ions could react with impurities in the device chamber, such as water, oxygen and solid insulators like epoxy resins. Products include SO<sub>2</sub>F<sub>2</sub>, SOF<sub>4</sub>, SOF<sub>2</sub>, SO<sub>2</sub>, S<sub>2</sub>F<sub>10</sub>, H<sub>2</sub>S, CO<sub>2</sub>, CF<sub>4</sub> and HF [26].

Table 2-2 Toxicity of byproducts of SF<sub>6</sub>. Source: [25] Table 2-2 shows the toxicity of some of these byproducts using the lethal concentration with 50 % mortality as the metric. Many of these are indeed toxic, and also potent acids.

**Table 2-2 Toxicity of byproducts of SF<sub>6</sub>. Source: [25]**

| <b>Product</b>                 | <b>LC50</b>     |
|--------------------------------|-----------------|
| SOF <sub>2</sub>               | -               |
| SO <sub>2</sub> F <sub>2</sub> | 991ppm/4 hours  |
| SO <sub>2</sub>                | 2520 ppm/1 hour |
| HF                             | 1276 ppm/1 hour |
| S <sub>2</sub> F <sub>10</sub> | 193 ppm/1 min   |
| SOF <sub>4</sub>               | -               |

The decomposition of SF<sub>6</sub> limits the range of technologies that can be used along with it. For example, silicon insulators must be avoided to not produce SiF<sub>4</sub>, which is also highly toxic, and galvanized materials are not optimal because they could be damaged through corrosion by the acidic compounds such as HF.

The potential problems with the toxicity of the decomposition components have been pointed in analysis of switchgears, for example by Tian et al., (2020) [22]. However, SF<sub>6</sub> has been considered safe to use because it itself is nontoxic, there is very limited exposure to humans as it is in a sealed enclosure, and many of these products are recombined again in SF<sub>6</sub> due to its self-regeneration properties, not reaching dangerous concentration levels.

### **2.1.5 Impact on climate change**

SF<sub>6</sub> is a very potent greenhouse gas. According to the Intergovernmental Panel on Climate Change (IPCC) report of 2013 [2], its GWP is 23,500 times greater than CO<sub>2</sub> in a 100 years time horizon. This means that emitting 1 kg of SF<sub>6</sub> is equivalent to emitting 23.5 tons of CO<sub>2</sub>. Furthermore, thanks to its chemical stability, it has a lifetime of 3,200 years (some studies estimated it lower at around 1,400 years ([27], [28])). This is much higher than the 100 year horizon used in the evaluation, and thus the impact could be much greater long-term.

Given these values, SF<sub>6</sub> is one of the gases affected by the Kyoto Protocol.

## **2.2 CURRENT ELECTRICAL EQUIPMENT**

SF<sub>6</sub> is used in a variety of electrical devices: gas insulated lines (GIL), gas insulated switchgear or switching stations (GIS), circuit breakers, disconnectors, current transformers and others. In Asia and sometimes in the USA, it is also used in transformers. However, this is very rare in Europe, where most transformers are oil-insulated [29].

This equipment can be classified according to its rated voltage and current, the maximum level it can withstand in continuous long-term operation. Thus, the equipment can be divided in Low Voltage (LV) for local distribution of electricity (up to 1 kV), Medium Voltage (MV) for regional distribution (up to 52 kV), and HV for transmission (52 kV and higher), as it is defined in the power grid. The equipment has a different design depending on the category.

SF<sub>6</sub> is widely used in both levels. However, in MV, alternatives have been more readily available and are already implemented in the system: oil, solid insulators

and air for insulation, and vacuum for arc quenching. Although they do not surpass the properties of SF<sub>6</sub>, they are viable options in practice.

### Impact on each level.

In the power system stations operating at MV are much more numerous. Burges et al., in their report for the German system [29] identify 2.5 million functional units at MV, compared to 25,000 at HV and 3,000 at EHV. However, when speaking of SF<sub>6</sub> emissions, the HV-sector has a much higher impact, both in production and operation, as seen in Figure 2-6.

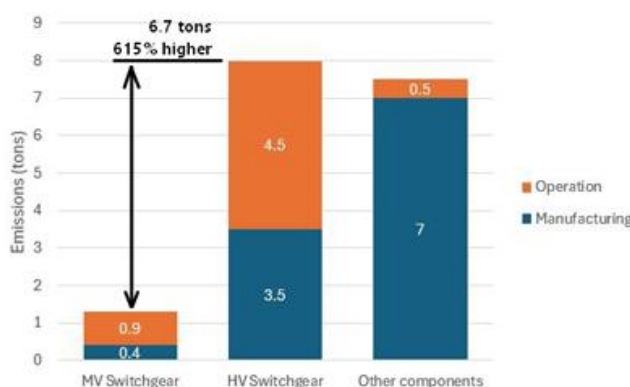


Figure 2-6 Emissions of SF<sub>6</sub> for different equipment in Germany, 2015. Source: own version based on [29]

The difference in emission factor during operation between the two levels can be easily explained by the pressure and volume: with more pressure, leakage increases. Differences in design of the enclosure also have an impact.

Figure 2-6 also shows that the highest emissions for production are under 'other equipment'. This includes current transformers, capacitors, bushings, etc. The information for these devices is, however, less traceable and more lacking

#### 2.2.1 Switchgear

A switchgear is a combination of electrical switches (circuit breakers and disconnectors) used to make switching operations in the equipment connected to it. It can open certain switches to electrically isolate and de-energize the associated devices, necessary for control and maintenance work. It also supports protection functions by incorporating automatic circuit breakers that open in case of a fault, clearing it downstream. It is widely used in substations to connect buses.

If these devices are encased in a metallic enclosure using some gas as an insulator medium, it is referred to as a GIS. Currently, SF<sub>6</sub> is the main gas used in GIS. If not, it uses the air at atmospheric pressure as insulation and it is referred to as an Air Insulation Substation. Examples of these substations can be seen in Figure 2-7.

Switchgears can also incorporate other devices beyond switches. They will usually have instrument transformers to measure current and voltage, and bushings and surge arresters for protection. These devices are explored in Section 2.2.2.

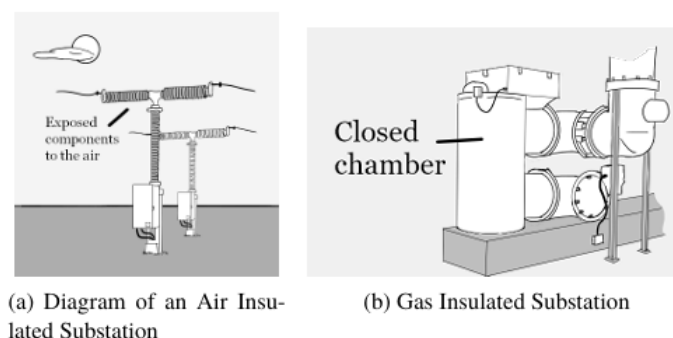


Figure 2-7 Examples of HV AIS and GIS

### Medium Voltage Switchgears.

MV-switchgears are encased in a grounded enclosure, as the one seen in Figure 2-8. For GIS, they have a sealed pressured system, pressurized between 1.3 and 1.8 bar [29]. This configuration offers the least leakage rate, with an expected value of 0.1% per year [29]. The expected lifetime is 40 years and it does not require refilling.

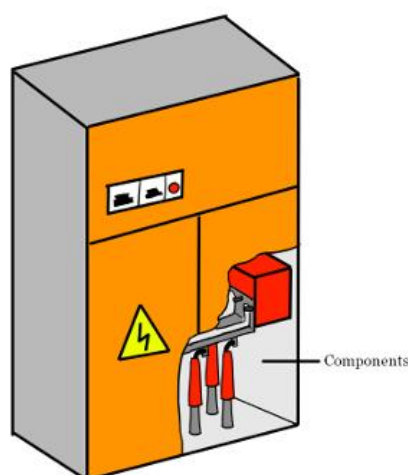


Figure 2-8 Diagram of a SF<sub>6</sub>-gas insulated medium voltage switchgear

It is used both in primary distribution in stations transforming from HV to MV, and in secondary distribution in stations transforming from MV to LV. As many MV applications are close to population centers, GIS are preferred for its compactness. 20% of the equipment installed for primary distribution in 2013 in Germany used SF<sub>6</sub> as its insulator medium, 35% for secondary distribution and 60% for generator installations [29].

### High Voltage Switchgears.

At HV both AIS and GIS are used. AIS, as it was explained before, has its components open, using air as the insulator. They have lower investment cost and do not emit GHG, but they are very surface-intensive to compensate for the lower dielectric strength of air. They also need more maintenance because they are exposed to the elements (e.g. dust, rain, pollution).

Modern HV GIS configurations are closed pressure systems. It has limited leakage compared to older models, but higher than MV devices. Leakage rate is standardized at 0.5% in the IEC 62271-203 [29], but in practice it is usually 0.1%. However, with time it can increase due to the damage or weakening of the flanges and seals [30]. HV GISs have much higher pressure than the MV-switchgear, reaching pressures up to 8 bar [29].

Although GIS can have higher installation costs, they require much less maintenance than AIS, reducing the cost during operation. They are also much more compact thanks to the higher dielectric strength of SF6. Substations of this kind have between 10-15% of the size of AIS. However, the use of SF6 has a negative environmental impact.

There are also hybrid configurations. They consist on AIS, with the bays and buses open to the air, but use gas-insulated elements, such as circuit breakers and switches. This combines some of the advantages of both options: the lower investment cost and lower environmental impact of AIS with the higher protection from environmental conditions and reliability of GIS. However, it is still very surface-intensive.

Contrary to the proportion seen in MV, HV substations are usually further away from population centers, making compactness less critical. Outdoor AIS are more common, with 15% of the equipment installed in 2013 in Germany using SF6 at HV, and only 6% at EHV [29].

#### Technical characteristics: ratings, size, lifetime, cost.

SF6 GIS are very established devices on the power system that have been researched and improved for decades. The state of the art currently reaches UHV up to 1,200 kV, and currents of 5,000/6,300 A for nominal operation and 80 kA for short circuit (short time, less than 3 s) [31] [32]. Table 2-3 shows values for models built by Hitachi Energy and Siemens Energy.

Table 2-3 Rated values of GIS. Source: [31,32]

|                | Model                 | ELK 04 | ELK 04 | ELK 14 | ELK 3 | ELK3 | ELK4 | ELK5 |
|----------------|-----------------------|--------|--------|--------|-------|------|------|------|
| Hitachi Energy | Rated voltage (kV)    | 145    | 170    | 300    | 420   | 550  | 800  | 1200 |
|                | Rated current (A)     | 3150   | 4000   | 4000   | 5000  | 5000 | 5000 | 5000 |
|                | Breaking current (kA) | 40     | 63     | 63     | 63    | 63   | 63   | 63   |
| Siemens Energy | Model                 | 8DN8   | 8DN8   | 8DN9   | 8DQ1  | 8DQ1 | -    | -    |
|                | Rated voltage (kV)    | 145    | 170    | 245    | 420   | 550  | -    | -    |
|                | Rated current (A)     | 3150   | 4000   | 4000   | 5000  | 5000 | -    | -    |
|                | Breaking current (kA) | 40     | 63     | 50     | 80    | 63   | -    | -    |

A GIS main components are the following, seen in Figure 2-9:

- The circuit breakers and their operating mechanism (Section 2.2.2).
- The disconnectors.
- The fast-acting earthing switches.
- The instrument transformers (Section 2.2.2).
- The terminals.

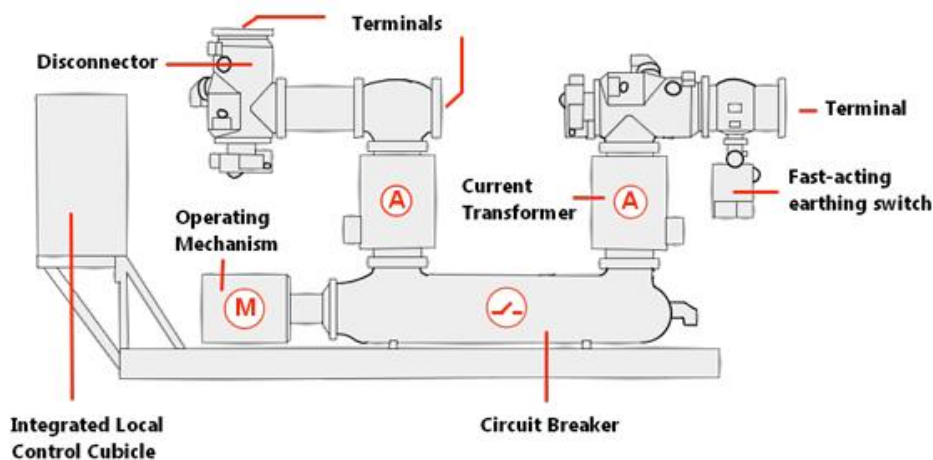


Figure 2-9 Components of GIS model ELK-3 420 kV. Source: own version based on [31]

GIS devices are very compact thanks to the higher dielectric strength of SF<sub>6</sub>. The ELK-04 model for 170 kV has dimensions of 4800x3000x1200 mm [31]. The ELK-3 for 420 kV is larger to accommodate for the bigger insulation requirements; its dimensions are 6980x3280x2160 mm for a double breaker bay and one chamber circuit breaker configuration. The models from Siemens are similar: 5500x3000x1000 mm for 170 kV and 5800x3800x2200 mm for 420 kV [32].

At 145 kV, a GIS uses 63 kg of SF<sub>6</sub> per bay for insulation, according to General Electric [33].

GIS have a technical lifetime expectancy of 40 years. They require very low maintenance; the period between re-fillings is at least 10 years if no exceptional circumstances occur [29], and the first major inspection is done at the half of the lifetime, 20-25 years [32]. In the NIR submitted by Sweden to the UNFCCC, the technical lifetime considered is slightly lower, 35 years [4].

For cost, Peak Substation Services—a packager of electrical equipment that operates in the USA—mentions an average price of \$500,000 for a single leg or bay of a half substation and a breaker rated for 138 kV [34].

### 2.2.2 Other devices

There are other components that can use SF<sub>6</sub> as an insulator beyond the switching devices. In this section, circuit breakers, instrument transformers, bushings and GIL are discussed.

The latter three deviate from switchgears, as there is no switching, only the dielectric strength is important when considering an insulator, and not the arc quenching capabilities. For this reason, these devices use frequently SF<sub>6</sub>-free alternatives such as oil.

However, they still use SF<sub>6</sub>, especially when installed in a GIS, and can have great impact. As seen in Figure 2-6, the yearly emissions during their manufacturing can equal those of the HV switchgear. Although the uncertainty of their emissions is higher due to less control.

#### Circuit Breakers.

Circuit breakers are an essential device in the power system. As it was previously said, they open circuits, cutting off the electrical current for protection and maintenance, and then close it back again to re-energize. They are present across all voltage levels, both in GIS and on their own in AIS.

SF6 is widely used in circuit breakers at HV, at both AIS and GIS. Burges et al., in their report studying the German system [29], find that 75% of the breakers used in outdoors applications are SF6 live tank breakers, whereas the remaining 25% use oil dead tank technology; the breakers used in GIS are, of course, gas-insulated breakers using SF6.

During operation, when the contacts are separated and the arc forms, the gas flow is used to extinguish the arc. The higher temperatures reached in the arc (an average of 1,000-3,000 K, and maximums of 12,000 K [25]) raise the pressure 3 to 4 times that of normal operation [30], which increases the dielectric strength as seen in Section 2.1.2.

They are composed of an operating mechanism and an interrupting chamber, as seen in Figure 2-9. The operating mechanism to separate or close the contacts is a spring-activated mechanical device. Different alternatives exist for energizing the spring; for example, Hitachi implements a hydraulic system [31], whereas Siemens uses an electric motor to give potential energy to one the spring, which then is transmitted to another during the operation, conserving it, [32].

The lifetime of circuit breakers is usually measured in number of operations, but it is expected to last for decades. For example, Siemens' live tank breakers have a lifetime of at least 10,000 operations and 50 years, with low maintenance requirements: an inspection at 12 years, and maintenance at 25 years [35].

Other technologies have been used besides SF6: the already mentioned oil dead-tank breakers, air-blast breakers, and vacuum breakers. They are briefly discussed in Chapter 3.

### **Instrument transformers (ITs).**

Instrument transformers are used for metering, using the ratio between two windings to reduce the voltage or current to levels that can be measured safely by another instrument.

The primary winding of the IT has the voltage level of the switchgear, so it needs a strong insulator to avoid voltage breakdown. In the case of GIS, its IT uses SF6 for insulation. When installed in a AIS, oil paper is usually used instead of SF6.

### **Bushings.**

Substations also use bushings, a protection device that serves as insulation at the connection of a bus into other equipment, such as a transformer or a GIS. It consists of an insulator enclosure, usually porcelain, which insulates the connection of the bus and the terminal. It can be filled with oil or SF6.

As with the ITs, only the insulation is necessary, and the arc-quenching capability is not. But it does circulate current, so heat dissipation is also important.

### Gas insulated lines.

GILs, as the name implies, are conductors enclosed in a cylindrical gas tight tube filled with an insulator gas, usually SF<sub>6</sub> or a mixture of 20% SF<sub>6</sub> / 80% Nitrogen. They can be used in transmission where overhead lines cannot be installed, or to directly connect a bus from a GIS to a transformer in a substation.

They are used in HV, existing solutions up to 1,100 kV and 6,300 A. The gas is at a pressure between 4.6 and 6.8 bar, with a leakage of 0.1% per year, similar to the switchgear [36].

## 2.3 MONITORING OF SF6 SWITCHGEARS

As it has been discussed, switchgears are a very robust piece of equipment. They have a long technical lifetime of around 40 years, with minor check ups/refilling only every ten years, and a major inspection only needed at twenty years under normal circumstances.

However, the criticality of the device as a part of the power grid, an essential service, makes monitoring of the utmost importance. The insulation properties of the gas are sensitive to pressure and ambient temperature. This must be measured frequently to ensure the correct functioning of the device and avoid or detect early electrical failures that can affect the power grid.

There is also the environmental impact of the gas. A break on the sealing or enclosure have a serious effect and must be dealt with rapidly. Regulations put emphasis on this aspect, requiring either an assurance of a leakage smaller than 0.1%, or gas pressure/density sensors (see Section 2.4).

Therefore, the use of sensors to monitor the conditions and detect leakage is implemented in the equipment. Table 2-4 summarizes the main indicators for each function.

**Table 2-4 Indicators and sensors for the different monitoring functions**

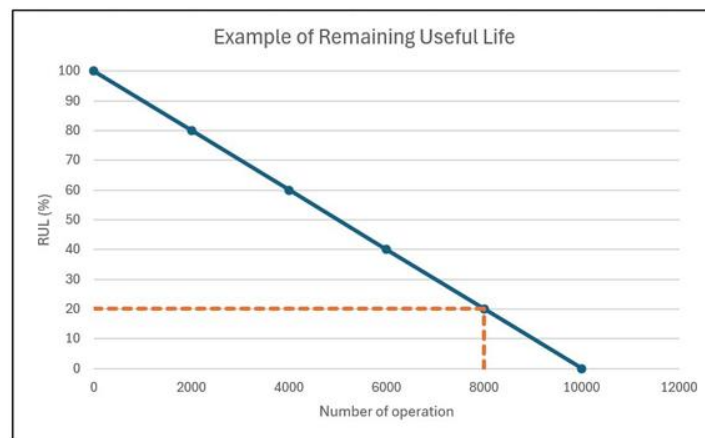
| Function         | Indicator                                                                 | Sensor                                                                                                 |
|------------------|---------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|
| Gas state        | Pressure, density and temperature                                         | Pressure sensor. Absolute density pressure with a quartz tuning fork.                                  |
| Machine state    | Position, stroke of springs, erosion of contacts, current and temperature | Infrared Sensors, Fiber optic sensors<br>Rotary and laser position sensors.                            |
| Leakage          | Pressure and density                                                      | Temperature sensors. CT                                                                                |
| Electrical event | Current, voltage, pressure, temperature and gas composition               | Pressure and density sensors<br>CT. VT. Pressure and temperature sensors. Chemical composition sensors |

### 2.3.1 Remaining Useful Life of circuit breakers.

Within the switchgear there is one critical part that needs special attention: the circuit breakers. Circuit breakers are a complex device composed of moving parts that can be more prone to mechanical failure than a rigid enclosure and sealing. Furthermore, they are exposed to the extreme conditions of electrical arcs when there is a short circuit: high currents in the order of kilo Amperes, high temperatures of thousands of Kelvin and pressure levels that can triple the nominal operation.

Atypical measurement of the state of the circuit breaker is the parameter Remaining Useful Life. Manufacturers do an accelerated test to see how many cycles or operations a device can make as breaking, and define that number as its technical lifetime; e.g., Siemens determined that the circuit breaker referenced before lasts at least 10,000 cycles [35]. Then, by detecting and counting operations, the number of cycles that the equipment has left can be known.

For example, Figure 2-10 shows a very simple linear relation between the number of operations and the lifetime. The equipment starts brand new, with no operation and a 100% of its life, and must be replaced after 10,000 cycles. When it has been opened and closed 8,000 times, it only has 2,000 cycles left. This means it has a RUL of 20%, and its maintenance and substitution can be planned accordingly. Although this example uses percentage of lifetime, other units can also be used, such as days or probability of failure.



**Figure 2-10 Example of a linear Remaining Useful Life (RUL) function**

This parameter is not only useful to evaluate the state of the equipment from a technical point, but can also be used to make economical decisions. Knowing the RUL of different components can help compare the cost-efficiency of making a repair, substituting that specific part of the whole device. Some of these applications are reviewed in Chapter 3.

### 2.3.2 Indicators and sensors

Indicators refers to the different properties or characteristics that the sensors measure, directly or indirectly, to give information about the state of the machine. In the switchgear, they can serve three functions:

- Monitor the state the of the insulating gas and the device.
- Detect leakage of the insulating gas.
- Detect electrical events (arcing, partial discharges, short-circuits).

Whereas the first point is a continuous operation which monitors the absolute value of the characteristics, the latter two refer to sudden events that present a change in the values. Some of the characteristics that the sensors must have are:

- Safe to use, not inducing short-circuits, electromagnetic interference or other harmful phenomena.
- Durable and stable under the operational conditions or more extreme conditions that are expected to be exposed to (e.g. temperature sensors should resist the higher temperatures reached during an electrical arc).
- Reliability and precision over time, as devices have long periods between maintenance sessions.

**Monitoring of the gas state** uses three main indicators: pressure, density and temperature, as they relate directly to the electrical performance of the insulator. They are measured directly with appropriate sensors. As they are local, one challenge it can present is the non-uniformity of the density and temperature distribution, making the measurement not valid for the whole compartment. Thus, multiple points of measurement can be recommended [30].

Current devices are based on pure SF<sub>6</sub>, and thus the measurements show directly the state of the gas. However, some of the alternatives use gas mixtures as a substitute. For these, the concentration of the gases becomes a new important indicator, as it is directly related to the dielectric strength and GWP of the mixture. The concentration can be calculated from pressure, density and temperature, but as each gas has its own partial pressure, the measurement set up becomes more complex [37].

There are two technologies of density sensors: reference gas comparison and quartz tuning fork.

Temperature sensors should be located in hot spots such as the conductors and busbar joints. There are many technologies available. Thermocouples are some of the simplest, consisting only on two metal wires and using the thermoelectric effect for the measurement; although they have been used in some research set-ups (e.g. Paul et al., (2014) [37]), they have low stability over time. Infrared temperature sensors or fiber optic sensors, although more expensive, have higher reliability over time.

**Monitoring of the device** includes the moving mechanical parts and auxiliary devices such as the electrical motors that move them. Important indicators are the position, the moving path, the stroke of the springs, and the erosion of the contacts for the mechanical aspects, and the electrical current and temperature for the actuators/motors. This uses position sensors (contact rotary sensors and non-contact laser position sensors), temperature sensors and current transformers [38].

**Leakage detection** is very critical due to the high impact of SF<sub>6</sub> as a GHG. Pressure and density can be used as indicators. When a point of escape is created, it connects the high-pressure chamber with the exterior (atmospheric pressure, 1 atm), and the pressure from the chamber will drop as the gas escapes. Pressure-density sensors can detect this drop, and raise the alarm communicating a leakage.

However, at first, this is a local effect around the escape point, and multiple points of monitoring have been recommended by some researchers [30]. This local effect

can be observed in Figure 2-11. This type of monitoring is referenced in the European regulations for SF<sub>6</sub> equipment (see Section 2.4).

A different approach is to measure the concentration of SF<sub>6</sub> in the room using infrared spectroscopy, that is, measuring the difference in the light absorption in the infrared range [30]. However, this method does not localize the leakage, as the room can contain more than one GIS.

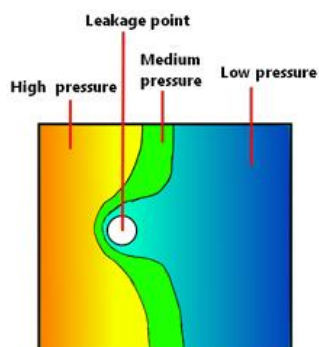


Figure 2-11 Diagram of the leakage process, pressure profile. Source: own version based on [30]

**Electrical event detection** helps evaluate the RUL of the device. They present in the form of an electrical arc that carries high energy, and it can wear and erode the contacts and age the insulation medium. The two direct indicators are the electrical magnitudes: voltage and current. The event is preceded by a sharp increase of voltage that surpasses the breakdown voltage of the medium, after which the electrical arc can form, producing a short circuit with a sharp increase of current. Both these magnitudes in the switchgear are measured with current and voltage transformers.

There is one obstacle: to differentiate between partial discharges and full breakdowns. Partial discharges have less energy and a lower impact on the RUL. Being able to differentiate between the two can lead to better estimations of the life expectancy.

There are also a number of indirect indicators that can also be used for this end. Both pressure and temperature see a sharp rise during the event which can trigger an alarm to communicate the event (Figure 2-12). Pressure can increase 3 to 4 times compared to nominal operation [30]. The electrical arc has an average temperature between 1,000 and 3,000 K, and a maximum at the core of 12,000 K [25].

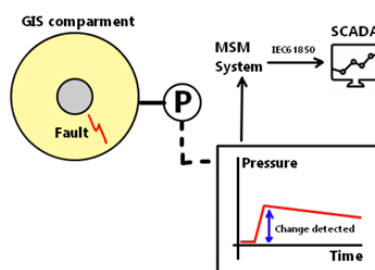
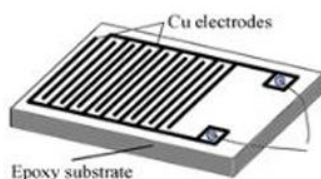


Figure 2-12 Diagram of the detection set-up for faults. Source: own version based on [39]

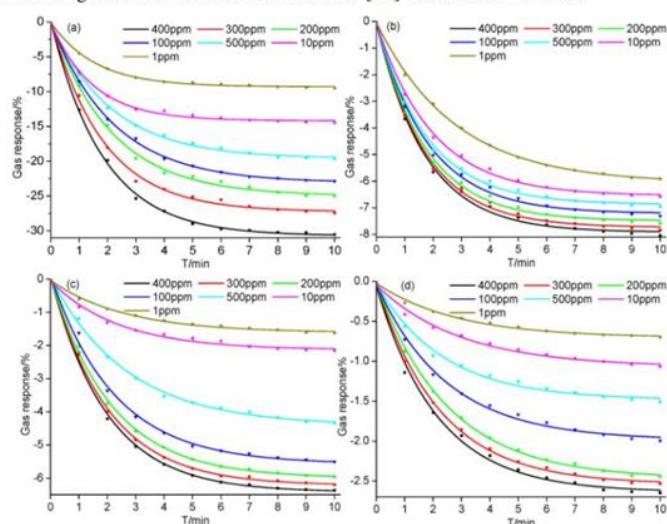
Some assessment methods are pulse current, ultrasonic sensors and ultra high frequency (UHF) sensors [26]. The circulation of a pulse current to detect defects is a simple method, but it cannot be used during online operation [26], which is a considerable disadvantage. Both ultrasonic and UHF sensors have high sensitivity and can locate the fault, but are susceptible to external factors such as vibrations producing noise in the measurement, and are do not work with thermal faults [26].

Decomposition component analysis looks to solve some of these issues: gives quantifiable results, highly reliable and works with thermal faults. The high temperature of the arc can also initiate the decomposition of SF<sub>6</sub> in other products such as SO<sub>2</sub>F<sub>2</sub>, SOF<sub>2</sub>, and CO<sub>2</sub>. The presence of these substances would indicate that an electrical event has happened.

Research on this area includes the use of photoacoustic sensors [40] and chemical sensors using materials with sensitivity and selectivity towards certain decomposition products, such as TiO<sub>2</sub> [41], SnO<sub>2</sub>/MWCNTs [42], and Ni-CNT [43]; the latter consist of an electrode with the sensitive material and uses the change of electrical resistance when exposed to the decomposition gases (Figure 2-13). They are small, economical, compact, and easily installed.



(a) Diagram of a Cu electrode on an epoxy substrate sprayed with a Ni-CNT solution to work as gas concentration sensor. Source: [43] under CC BY license.



(b) Change of resistance as a response to the gas over time for a Ni-CNT sensor. Source: [43] under CC BY license.

**Figure 2-13 Gas decomposition sensors**

### Current monitoring systems.

Looking into the devices used as examples in the previous section, by Siemens and Hitachi Energy, both of them already have monitoring systems installed.

Siemens switchgears have the Sensgear™ system. As seen in the brochure [32], this system includes various temperature sensors for different parts (cabinet, ambient), position sensors and counters for the switches, a gas density sensors, etc. It also monitors contact wear and erosion using SiCEA01 control, with alarms when certain levels are reached to program a maintenance visit [32]. Outside of this system, it also has a CT, available as a Low Power Instrument Transformer (LPIT) for lower volume and weight.

Hitachi Energy has available the modular switchgear monitoring system [39], which measures indicators for dielectric capabilities (pressure, temperature, moisture, leakage, and arc localization), mechanical aspects (travel curve, timing, contact speed), wear, and accessories.

One very important aspect of both systems is the communication with the operator. Both are compatible with IEC61850 and DNP3 communication protocols, and through this the state of the device can be observe at any moment.

## 2.4 CURRENT STATUS IN EUROPE

Countries in the EU-28 have to report their stock of GHG to the UNFCCC every odd year. Table 2-5 shows the total stock of SF<sub>6</sub> gas used in electrical equipment, calculated as the sum of the values given in the individual reports of each country. In the year 2020 there is installed a total of 11,648 tons of SF<sub>6</sub>, a 270% increase since 1990 due to the expansion of the power system.

Germany (3,075.28 tons), Spain (2,031.09 tons), United Kingdom (1,686.72 tons), Italy (1,619.40 tons), and France (1,154.24 tons) have the most, accumulating between them 82% of the total stock. Sweden is the seventh country with 2% of the total stock. Greece, Ireland, and the Netherlands report no use.

In Sweden, focusing on the power system (switchgears and circuit breakers), Energiföretagen Sverige reports 155 tons of SF<sub>6</sub> in 2021 with 0.24 tons of leakage, an implied factor of 0.15%. Even though the use of SF<sub>6</sub> has increased, the emissions factor has decreased from 0.40% in 2000 to the 0.15% in 2021 [3]. Table 2-6 shows the use of the gas in the last two decades.

In 1990, other industries or technologies with significant use of SF<sub>6</sub> were soundproof windows (1,032.95 tons), shoes and tires (243.96 tons), accelerators (138.48 tons), and small uses such as in the medical industry (0.03 tons) [44]. Contrary to the increase in electrical equipment during the last two decades, its use has dropped due to the regulations introduced. In 2020 only 639.73 tons are used in soundproof windows, and it is no longer used in shoes and tires [44].

Some doubts have been presented about these figures, as they seem significantly underestimated compared to other independent sources such as Emissions Database for Global Atmospheric Research (EDGAR), and top down methods that instead calculate emissions from empirical measurements of SF<sub>6</sub> concentration in the troposphere [13] [45].

Table 2-5 SF<sub>6</sub> stock in electrical equipment in the EU-28. Data from UNFCCC, CRF Tables [46]

| Year | EU-28 SF <sub>6</sub> stock [tons] | Sweden SF <sub>6</sub> stock [tons] |
|------|------------------------------------|-------------------------------------|
| 1990 | 3,159.55                           | 59.78                               |
| 1995 | 4,281.93                           | 69.75                               |
| 2000 | 5,176.47                           | 101.25                              |
| 2005 | 6,408.99                           | 135.64                              |
| 2010 | 8,265.40                           | 183.93                              |
| 2015 | 9,882.66                           | 229.29                              |
| 2020 | 11,648.47                          | 253.28                              |

Table 2-6 SF<sub>6</sub> stock in the power system, Sweden. Data from Energiföretagen [3]

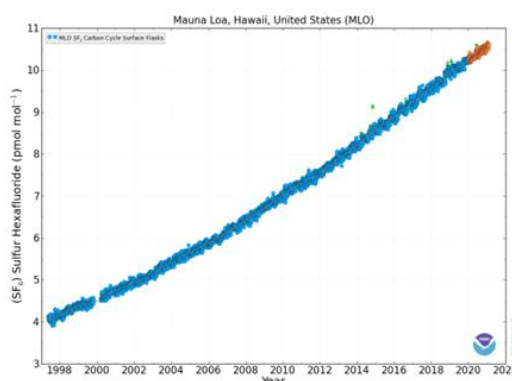
| Year | SF <sub>6</sub> stock [tons] | Leakage [tons] | Leakage [%] |
|------|------------------------------|----------------|-------------|
| 2000 | 28                           | 0.11           | 0.40%       |
| 2005 | 77                           | 0.33           | 0.42%       |
| 2010 | 108                          | 0.34           | 0.32%       |
| 2015 | 124                          | 0.33           | 0.27%       |
| 2020 | 153                          | 0.24           | 0.16%       |
| 2021 | 155                          | 0.24           | 0.15%       |

Table 2-7 Comparison of SF<sub>6</sub> and GHG (without Land Use) emissions in the EU, in units of ktons of CO<sub>2</sub> equivalent. Data from UNFCCC [47]

| Year | GHG (ktons CO <sub>2</sub> eq.) | SF <sub>6</sub> (ktons of CO <sub>2</sub> eq.) | SF <sub>6</sub> (%) |
|------|---------------------------------|------------------------------------------------|---------------------|
| 1990 | 4,860,553.45                    | 10,005.60                                      | 0.21%               |
| 1995 | 4,554,457.56                    | 14,225.59                                      | 0.31%               |
| 2000 | 4,446,889.20                    | 8,809.21                                       | 0.20%               |
| 2005 | 4,537,296.30                    | 6,960.32                                       | 0.15%               |
| 2010 | 4,176,794.13                    | 5,856.24                                       | 0.14%               |
| 2015 | 3,809,061.47                    | 5,920.14                                       | 0.16%               |
| 2020 | 3,300,463.61                    | 5,408.37                                       | 0.16%               |
| 2021 | 3,468,394.08                    | 4,837.80                                       | 0.14%               |

UNFCCC reports that in 2020 4,837 ktons eq. CO<sub>2</sub> have been emitted from SF<sub>6</sub> sources [47]. This value represents a very small share of the total GHG emissions, only 0.14%. Furthermore, it has been significantly reduced since its peak in 1995, thanks to the regulations limiting its use and improvement of the technology to avoid leakage.

However, due to its long lifetime in the atmosphere of over 3,000 years, the amount present in it has steadily increase during the last 30 years, with an increase as high as 20% between the years 2010 and 2015, as seen in Figure 2-14.

Figure 2-14 SF<sub>6</sub> concentration in the atmosphere. Source: Mauna Loa Observatory, Public domain use

### 2.4.1 Regulations

Even if the total emissions are small compared to other GHG sources, its high GWP makes it a significant environmental hazard if kept unchecked. For this reason, it is included under the fluorinated gases (F-gases), along with hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), in the Kyoto Protocol. Thus, it has been subjected to several regulations in the EU with the objective to reduce its use.

The first of these regulations is "Regulation (EC) No 842/2006" [48], issued in 2006. Following the goals of the Kyoto Protocol, it set as an objective "(...) 8% reduction in emissions of greenhouse gases in the period from 2008 to 2012 compared to 1990 levels, and that, in the longer-term, global emissions of greenhouse gases will need to be reduced by approximately 70% compared to 1990 levels." [48]. To achieve this, it restricts the marketing and use of technologies with fluorinated gases "where viable alternatives are feasible" [48].

Annex II details a list of applications where the use of this gases is prohibited. Of the industries where SF6 is used, windows for domestic use and others have been prohibited since July 2007 and July 2008 respectively, footwear July 2006, and tires July 2007. Furthermore, Article 8 specifically refers to the prohibition of SF6 in magnesium die-casting (except when below 850 kg per year) since January 2008.

Its use in switchgears is not prohibited as there are not "viable alternatives". However, it is regulated. Article 4 establishes the responsibility of the operator in the recovery at the end of its lifetime. Further articles regulate the training needed by the operators, the reporting of the amounts, and the labeling of the products.

This regulation was updated in 2014 with the implementation of the "Regulation (EC) No 517/2014" [49]. Considering the conclusions from the Forth IPCC, this new regulation looked to reduced GHG emissions by 80% to 95% in 2050 compared to values of 1990. Specifically, in regards to F-gases, it set as goals a reduction "(...) by 72% to 73% by 2030 and by 70% to 78% by 2050, compared to 1990 levels" [49].

To achieve this, it strengthens the regulations of 2006. Switchgears under it are subject to more strict reports of inventory, and to leak checks unless one of the following conditions is fulfilled:

- It has a leakage rate less than 0.1%.
- It is equipped with a pressure/density monitoring device.
- It contains less than 6 kg of F-gas

Even though the list of prohibited use is expanded, it still does not affect switchgears or other electrical equipment.

Finally, the regulation is currently subject to an update, the proposal of which started on 2022. The initial proposal received various counter arguments in its impact to the power system, such as the letter of recommendations by ENTSO-E [8], warning that the alternatives are not mature enough at the current date. The European Parliament has approved a legislative resolution on the 16th of January of 2024 [50].

This new regulation finally prohibits the installation of new switchgears that use F-gases with a warming potential higher than 1 up in Article 13 [50]. In MV it is prohibited to 24 kV from January 2026, and up to 52 kV from January 2030. And in HV up to 145 kV and 50 kA from January 2028, and above said threshold from January 2032. However, it derogates the previous limitation, increasing it to a GWP of 1,000 in Paragraph 11 [50], and over that threshold in Paragraph 12 [50], if no bids with those requirements are received. It also prohibits the use of SF6 in maintenance from January 2035 unless reclaimed or recycled.

## 2.5 SUMMARY

Sulfur hexafluoride (SF6) is an inorganic compound widely used in HV equipment for its unique combination of properties:

- **Gas state:** it has a low boiling point of -63.8°C, and a critical point of 45.5°C at 37.6 bar. This allows its operation in gaseous state at high pressures, which is better for insulation.
- **Dielectric strength:** the big electronegativity of its fluorine atoms gives SF6 a high dielectric strength of 885 kV/(cm MPa), three times higher than air. This allows for more compact systems, as bigger separation between contacts is not needed.
- **Current interruption:** a mixture of good dielectric strength, thermal conductivity and convection and fast dielectric recovery makes SF6 the best medium for current interruption at HV. Current devices reach levels of 550 kV and 63 kA.
- **Decomposition:** SF6 is thermally stable below temperatures of 800 K. In the conditions of operation, it is considered nontoxic.
- **Environmental impact:** SF6 has the highest GWP, at 23,500 times higher than CO2 and between 1,000 and 3,000 years of lifetime in the atmosphere.

It is used in equipment such as gas insulated switchgears, gas insulated lines, instrument transformers, bushings and circuit breakers. This project studied HV GIS because they have the highest impact on emissions.

These devices consist of switches used to isolate sections of the grid. They were introduced in the 1970s and have had a lot of development. Currently, they reach voltage levels of 1,200 kV, at which SF6 is the only current viable option. They operate at high pressures of 8 bar to improve insulation, but this increases the risk of leakage; leakage rate is standardized at 0.5% per year, but manufacturers tend to assure a lower value of 0.1%. They have long technical lifetimes of 40 years and low maintenance. In Germany, 2013, 15% of the equipment in HV used SF6 [29].

Circuit breakers are also quite important in the use of SF6. In Germany, 2013, 75% of them used SF6. When they are a component of the switchgear they are also one of the critical points for its lifetime, as the moving parts and higher pressure/temperature during arc interruption make it more vulnerable to wear and tear. Typical values given by manufacturers at this levels are 10,000 cycles and 50 years.

Pressure, density and temperature monitoring is key to both control the insulation capabilities (as dielectric strength is proportional to pressure, and the three together indicate the state of the compound) and to detect leakage. Other important indicators can be the position and erosion of moving parts in the circuit breaker, current and voltage, and the composition of the gas (as the existence of products of decomposition indicate high energy events). Current devices have sensors installed for these indicators. Two key factors of their monitoring systems is the detection of events (e.g. triggering an alarm if pressure rises above a threshold), and the communication with the operators over protocols such as IEC61850.

In Europe in 2020 there was installed 11,648 tons according to data from the UNFCCC, lead by Germany, Spain, UK, Italy and France. Sweden has installed 253.28 tons of SF<sub>6</sub> in its electrical system. Different European regulations have limited the use of the gas in different industries since 2006. Currently, it is only permitted in the electric grid for lack of viable alternatives. But a new regulation under study [50] is going to prohibit the installation of new devices using the gas between 2026 and 2032. This requires the study of SF<sub>6</sub>-free alternatives.

### 3 Study of new alternatives

**This chapter continues the literature review, covering the new technologies, but it does not serve simply as background, adding a critical eye that serves as the initial conclusions in regard to the research questions 2 and 3. This information is used to decide which technologies are included in the replacement plans studied.**

It shows the current state of the art analysis of the different alternatives for SF<sub>6</sub>. This uses both manufacturer's publications, like Kieffel et al., [18], that compare their solution to SF<sub>6</sub> and other competitive SF<sub>6</sub>-free alternative, as well independent studies, like Tian et al., [22]. It also looks into some SF<sub>6</sub> devices built by Siemens and Hitachi, comparing them to the SF<sub>6</sub> technologies, and their implementations on the field.

Finally, some machine learning tools are presented, and their synergy with the proposed plans is discussed.

#### 3.1 ALTERNATIVE TECHNOLOGIES

In the last decade, the search for more environmentally-friendly gases to substitute SF<sub>6</sub> has been a focus point for research. There has been a lot of analysis in already existing alternatives, such as air, and in developing new products. In order to be a viable substitute, the gas should have similar characteristics to those seen in Section 2.1.

- **Gas state:** the gas should have a low boiling point and a high vapor pressure, so that it stays in gaseous form in conditions of low temperature and high pressure. Specifically, the boiling point should at least be lower than -25°C, as the norm requires.
- **Insulation properties:** it should have high dielectric strength and breakdown voltage.
- **Arc quenching capabilities:** this includes fast times for current interruption, good thermal properties (dissipation and specific heat) to evacuate the heat produced in the event, low electrical conductivity and fast dielectric strength recovery.
- **Decomposition:** the reactivity of the gas should be low (thermally stable) to increase its lifetime. In case that there is decomposition, the products should not be harmful or toxic, and should be compatible with the materials of the equipment.
- **Impact:** the gas should be environmentally friendly. It must have no Ozone Depletion Potential (ODP), and low GWP. It should also be safe to use, preferably not inflammable not explosion risk.

However, not all the alternatives need to cover all of the criteria, with exception of safety and environment. As seen in Section 2.2.2, for example, not all devices need

good arc extinguishing properties. There is flexibility in the gases use for different applications. Table 3.1 summarizes the characteristics of each alternative.

**Table 3-1 Alternative insulating mediums compared to SF6**

| Alternative  | Insulation  | Breaking              | Impact (GWP) and toxicity        | Boiling temperature    | Other comments       |
|--------------|-------------|-----------------------|----------------------------------|------------------------|----------------------|
| Air, N2, CO2 | Low         | Bad, CO2 up to 145 kV | GWP 0 (1 for CO2)<br>Non-toxic   | Low                    | Devices up to 145 kV |
| SF6 mixture  | Medium-low  | Good                  | High GWP, non-toxic              | Low                    | -                    |
| PFCs         | High        | -                     | High GWP, non-toxic              | High                   | -                    |
| PFKs         | High        | Good                  | Low GWP,<br>C4-FK is toxic       | High                   | Used in MV           |
| CF3I         | High        | None                  | Low GWP, toxic                   | High                   | -                    |
| C4-FN        | High        | Good                  | High GWP<br>Toxicity under study | High                   | Needs buffer gas     |
| C4-FN        | Medium-high | Good                  | Lower GWP than SF6               | High, lower than C4-FN | Devices up to 420 kV |

### 3.1.1 Atmospheric gases (N2, CO2, and air) and SF6 mixtures

Given their availability, atmospheric gases such as N2 and CO2 have been studied as insulating medium even before the introduction of more strict F-gas regulations (e.g., [51]). And more recently the study has expanded to new alternatives such as dry-air [52].

These gases are very economical and easily available as they are simpler compounds present on air. They also are safe to use, non-toxic, and have very low environmental impact. N2 does not contribute to global warming, whereas CO2 has a GWP of 1, much less than SF6, and both have a low ODP. They also have very low boiling temperatures.

Dry air has the highest dielectric strength, followed by N2 (32.9 kV/(cm bar) [53]) and CO2 (30.1 kV/(cm bar) [53]). At 1 MPa, the breakdown voltage of N2 equals that of SF6 at 0.5 MPa [22]. However, the breakdown voltage of CO2 is more stable than of N2. Both gases suffer from bias voltage, meaning that their strength is reduced in the presence of positive polarity waveform ([22], [53]).

Of the three gases, CO2 has the better arc interruption capabilities, but they are still worse than those of SF6. At the same pressure, the thermal shutdown of CO2 is 50% that of SF6, and can be improved by 30% with modifications [22]. It can potentially be used in circuit breakers at HV up to 145 kV.

Atmospheric gases are mostly limited to MV applications. Their dielectric strength is 2.5- 3 times lower than SF6, as seen in Figure 2-3. To achieve the same performance as the current equipment, either pressure or volume would need to be increased by that factor.

An increase of pressure would require to adapt the mechanical structure to the new conditions, reinforcing the encasing to support the higher pressure. This has both an economical impact and a higher footprint in the manufacturing phase. The same happens with an increase of volume, which furthermore it also impacts the physical location of the installation and might require new construction work.

The Life Cycle Analysis done by Hitachi Energy, which is discussed in following sections, confirms this: a 145 kV GIS based on technical air has a manufacturing footprint of 36,936 kg CO<sub>2</sub> eq., compared to 24,127 kg CO<sub>2</sub> eq. emitted for an SF<sub>6</sub> GIS [12].

**Table 3-2 Properties of atmospheric gases. Source: [53]**

| Gas             | Relative dielectric strength to SF <sub>6</sub> | Toxicity  | GWP | Boiling temperature [°C] |
|-----------------|-------------------------------------------------|-----------|-----|--------------------------|
| Air             | 0.37 - 0.40                                     | Non toxic | 0   | -                        |
| CO <sub>2</sub> | 0.32 - 0.37                                     | Non toxic | 1   | -79                      |
| N <sub>2</sub>  | 0.34 - 0.43                                     | Non toxic | 0   | -196                     |

Mixtures of SF<sub>6</sub> with some of these compounds as a buffer gas have also been studied. The concept is that each would cover for the shortcomings of the other: SF<sub>6</sub> increases the dielectric strength and breaking properties, helping to keep the pressure and volume lower, whereas the atmospheric gas reduces the GWP and boiling temperature of the mixture. Mixtures of SF<sub>6</sub> and N<sub>2</sub> are actually in use in equipment such as Gas Insulated Busbars [18].

However, the results are not satisfactory for HV GIS. A mixture of 10% SF<sub>6</sub> and 90% N<sub>2</sub> has only a dielectric strength 0.59 that of SF<sub>6</sub>, and a GWP of 8650 [18], still considerably high, and higher than the threshold proposed by ENTSO-e (GWP of 2000, [8]).

### 3.1.2 Fluorinated gases

Same as with SF<sub>6</sub>, the presence of fluorine makes fluorinated gases very electronegative and, therefore, good candidates for an insulating medium. This group includes Perfluorocarbons (PFCs) and Perfluoroketons (PFKs), among others.

#### Perfluorocarbons (PFCs).

PFCs are halogen gases composed only of carbon and fluorine atoms. Research has focused on four compounds: c-C<sub>4</sub>F<sub>8</sub>, C<sub>3</sub>F<sub>8</sub>, C<sub>2</sub>F<sub>6</sub> and CF<sub>4</sub>. They have dielectric strengths comparable or even superior to SF<sub>6</sub> with lower warming potential. However, the GWP is still considerably high, in the range 6,000- 10,000 (see Table 3-3). When analyzed individually, further disadvantages arise.

**Table 3-3 Properties of PFCs. Source: [53]**

| Gas                             | Relative dielectric strength to SF <sub>6</sub> | Toxicity  | GWP   | Boiling temperature [°C] |
|---------------------------------|-------------------------------------------------|-----------|-------|--------------------------|
| c-C <sub>4</sub> F <sub>8</sub> | 1.11 – 1.80                                     | Non toxic | 8,700 | -6                       |
| C <sub>3</sub> F <sub>8</sub>   | 0.88                                            | Non toxic | 7,000 | -36.6                    |
| C <sub>2</sub> F <sub>6</sub>   | 0.67 - 0.90                                     | Non toxic | 9,200 | -78                      |
| CF <sub>4</sub>                 | 0.39 - 0.62                                     | Low       | 6,500 | -128                     |

The first compound, c-C<sub>4</sub>F<sub>8</sub>, is specially interesting because it has better insulation performance than SF<sub>6</sub>, with a dielectric strength 1.11 to 1.80 times higher [53]. However, its boiling point is very high, -6°C [53].

To solve these issues, mixtures of PFCs with nitrogen have been studied. They follow the same principle as SF<sub>6</sub>/N<sub>2</sub> mixtures: the PFC offers the dielectric

strength, whereas the nitrogen reduces the GWP and the boiling point. With increases in pressure, these mixtures can reach performances comparable to SF<sub>6</sub>. For example, a mix of 20% C<sub>3</sub>F<sub>8</sub>- 80% N<sub>2</sub> with an increase of pressure of 1.59 times has the same dielectric strength than SF<sub>6</sub> with only 0.9% of the warming potential. However, the increase of pressure require is significant and can impact the manufacturing phase as it happens with atmospheric gases.

### **Perfluoroketons (PFKs).**

Fluoroketons are compounds with the generic formula C<sub>n</sub>F<sub>2n</sub>O. Two gases, C<sub>5</sub>F<sub>10</sub>O and C<sub>6</sub>F<sub>12</sub>O, or C<sub>5</sub>-FK and C<sub>6</sub>-FK, were proposed as alternatives by ABB in 2015 [22] [54].

Both of them have significantly higher dielectric strength than SF<sub>6</sub> (2 times higher, 1840 kV/(cm MPa) [55] for C<sub>5</sub>-FK, and 1.7 times higher [18] for C<sub>6</sub> FK) and almost no environmental impact thank to a very low lifetime in the atmosphere (less than a week for C<sub>6</sub>-FK [18]), meaning their GWP ≤ 1 [18] [53].

However, their boiling point is extremely high for the application, 26.9°C [55] and 49°C [22] [53] respectively. They cannot be used alone, and need a buffer gas to reduce the boiling point. In mixtures, C<sub>5</sub>-FK shows better performance than C<sub>6</sub>-FK. As it happens with the other cases, it needs an increase of pressure to reach the performance of SF<sub>6</sub>. A mixture of 5% C<sub>5</sub>-FK and dry air at 7 bar has the same dielectric strength than pure SF<sub>6</sub> at 4 bar [22].

Another PFK, C<sub>4</sub>-FK, has a lower boiling point, 0°C. However, it is toxic, with a LC<sub>50</sub> (lethal concentration of 50% mortality) of 200 ppm. It is unsuitable for industrial applications.

The arc interruption capabilities of C<sub>5</sub>-FK mixtures are equal to SF<sub>6</sub>. However, they do not posses the recombination properties that the latter has after the event.

Perfluoroketons have seen application in MV [22], but the issues with the boiling point have limited their application at HV.

### **Trifluoriodomethanes (C<sub>3</sub>FI).**

CF<sub>3</sub>I shares some of the properties that the previous compounds presented, as it follows the same generic formula C<sub>p</sub>F<sub>q</sub>X<sub>r</sub>. It has insulation capabilities comparable to SF<sub>6</sub> and a very low GWP around 1 with a lifetime in the atmosphere less than a day [53], which makes it a very interesting alternative.

Its boiling point is high, -22.5°C [53], which increases to 25°C at 5 bar [53], realistic pressure levels for a GIS. Therefore, it has to be used along a buffer gas. Nevertheless, the mixtures still keep good insulation capabilities (see figures from [56]). Experiments with the mixture in a 400 kV GIL conclude that it can be used as an insulator, but that its interruption capabilities are inadequate [22].

However, the gas is classified as a carcinogenic substance, a mutagen type 3, and moderately toxic [18] [22] [53]. Therefore, its use in industrial application is almost certainly discarded.

### 3.1.3 New fluorinated gases: C4-FN

C4-FN [57] is a fluoronitrile with the chemical formula  $C_4F_7N$  developed by the company 3M<sup>TM</sup> under the name NOVEC<sup>TM</sup> 4710 in 2016 [18]. Since then, its good performance has drawn attention from the industry and actual applications are being built.

Its dielectric strength is superior to SF<sub>6</sub> (Figure 3-2). At 1 bar, the breakdown voltages is 27.5 kV [57].

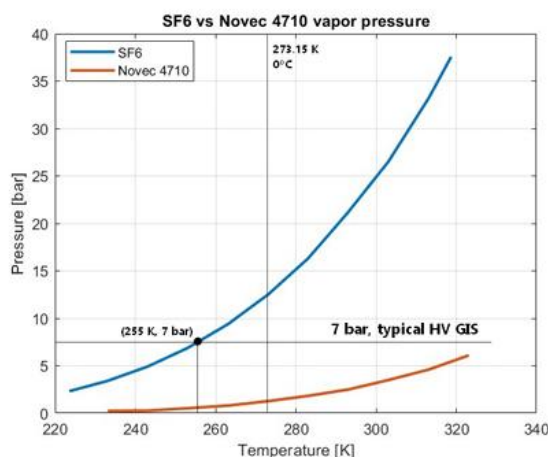


Figure 3-1 Vapor pressure of NOVEC<sup>TM</sup> 4710 compared to SF<sub>6</sub>. Source: own work, data from [57]

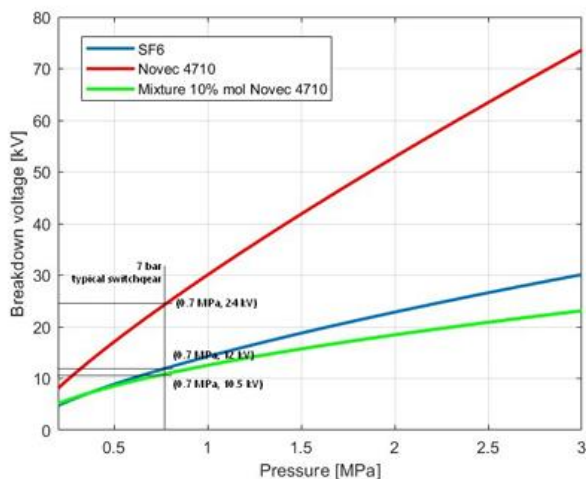


Figure 3-2 Dielectric strength of NOVEC<sup>TM</sup> 4710 mixtures compared to SF<sub>6</sub>. Source: own version, data from [57]

It has a warming potential of 2,100 with a lifetime of 30 years [57] in the atmosphere, significantly less than the 23,500 and over 3,000 years of SF<sub>6</sub>. However, it is still high. Along with a high boiling point of -4.7°C [57], it needs a buffer gas.

3M<sup>TM</sup> found that CO<sub>2</sub> was the best alternative for the buffer gas for its arc quenching capabilities [18]. The mixtures have received the name g3. These still have performances comparable to SF<sub>6</sub>, as seen in Figure 3-2. Between 18% and 20% of C4-FN it is equal to pure SF<sub>6</sub>. In a typical GIS application, with a minimum

temperature of -25 °C, g3 reaches 90% of the strength of SF6, and can be incremented with changes in design such as a higher operating pressure [18].

Breaking tests have also been done. In a continuous 100 s test, a mixture of 4% C4-FN had an average arcing time of 12 s, shorter than pure SF6 at 15 s [18]. The experiments done by Gautschi et al., [58] agree with this results: in their bus transfer current switching the arc lasted for 10.9 ms compared to 11 ms for SF6, although the standard deviation is considerably higher for g3, and in their induced current switching test, 3 ms compared to 3.1 ms. The mixture is apt to operate in circuit breakers at HV.

The buffer gas also helps reduce the warming potential. An application at a 420 kV GIB had a GWP of 330 using g3 [18]. This value is significantly less than SF6, and it is below the threshold recommended by ENTSO-e (2000, [8]). However, it is still higher than the objective levels in the most strict regulations [50].

Independent research studies such as Tian et al., (2020) [22] and Li et al., (2019) [59] have shown some concern about the safety of the gas. The cyano group (CN) in the molecule is a potential hazard of the compound or its byproducts after thermal degradation.

Nevertheless, mixed with CO2, that is, g3, it is not considered toxic under current regulations, having slightly lower LC50 levels to SF6. Kieffel et al., find values between 100,000 ppmv and 190,000 ppmv for 10%-4% NOVEC™ 4710 respectively [18]. Similar levels are confirmed by Pohlink et al., (2016) [60]. Tables 3.4 and 3.5 show the toxicity values for the mixtures and byproducts.

g3 is also not flammable and safe to use.

**Table 3-4 Toxicity levels of NOVEC™ 4710 mixtures. Obtained from: [59]**

| Mixture             | LC50(4-h) on rats, ppm |
|---------------------|------------------------|
| 100% C4-FN          | 10,000 - 15,000        |
| 100% CO2            | >300,000               |
| 4% C4-FN - 96% CO2  | 160,000 - 212,000 [60] |
| 10% C4-FN - 90% CO2 | 95,500 - 100,000 [60]  |

**Table 3-5 Toxicity levels of byproducts of NOVEC™ 4710 mixtures. Obtained from: [59]**

| Byproduct                        | LC50(4-h) on rats, ppm |
|----------------------------------|------------------------|
| CO                               | 1,880                  |
| CF <sub>3</sub> CN               | 250                    |
| C <sub>2</sub> F <sub>5</sub> CN | 2,730                  |
| C <sub>2</sub> N <sub>2</sub>    | 175                    |
| C <sub>2</sub> F <sub>4</sub> O  | 200                    |
| CF <sub>2</sub> O                | 180                    |
| C <sub>3</sub> F <sub>6</sub>    | 3,060                  |

Kieffel et al., (2016) [18], along their introduction of the compound, also presents results of various pilot applications. They tested the gas in a 145 kV GIS (including the circuit breaker), a 420 kV GIB, and a 245 kV Current Transformer.

Since then, the gas has been installed in many substations, and more studies have been done in functioning equipment. GE Grid Solutions published their analysis of the equipment after two years of operation [61]. They found no changes on the gas

composition, and concluded that gas monitoring is not necessary and that maintenance can follow similar schedule as with SF6 devices.

#### 3.1.4 Other alternatives

There are more fluorine gases under study, but for many of them the research is not yet mature and further studies are necessary to evaluate them.

One such gas is a hidrofluoroolefine, HFO-1234zeE, that has recently gained some interest. It has a dielectric strength close to SF6, in the range of 0.8-0.95 times, and low GWP of 6 [53]. The boiling point is high, -19.4°C, reaching room temperature of 20°C at 0.42 MPa [53]. It could be use on its own in MV in indoor applications, but for higher voltages a buffer gas would be needed. It is not adequate for current breaking [22], and some issues can arise from its decomposition during flashovers such as a solid carbon deposit that could lead to short-circuits [53].

#### 3.1.5 Alternatives for circuit breakers

As many of the proposed gases have good insulation properties but are bad at current breaking, other technologies have to be considered to use along them. As it was mentioned in the previous chapter, three types of SF6-free circuit breakers are already in used.

Oil circuit breakers utilize oil as the insulator and breaking medium in dead tank configurations. It is an old technology that was introduced in HV since the 1970s. They are still used in many old substations. However, they have lower dielectric strength than SF6 and vacuum, and present dangers of fire and explosions for its flammability, so they are not a good option moving forward.

Air-blast breakers uses compressed air propelled at high velocity through a nuzzle. This current of air separates the contacts and pushes the ionized gas to extinguished the arc; the air then stays in the chamber, providing good insulation thanks to its high-pressure. They can break high currents and operate at a HV level using non GHG such as air, or at least gases with low GWP like CO2. However, this technology works with very high pressures, up to 20 bar. This requires a big compressor system, which increases the size of the breaker, and high maintenance to prevent any leakages and drop of pressure. For these reasons, they are more expensive during operation than other alternatives.

Vacuum breakers contain the contact in a vacuum sealed medium. The vacuum medium has great insulation capabilities, only surpassed by SF6 at high pressures and after the arc breaking, it recovers its dielectric strength at very high rates. It can break currents up to 100 kA [32]. When the signal is triggered, the contacts separate. The resulting arc is contained by a magnetic field, and then extinguished. The contacts are shaped to produce a uniform electrical field.

Vacuum breakers have very low environmental impact, as they do not use GHG, and very low maintenance, as there is no issue with gas leakage as there is with air blast or SF6 breakers, being one of the cheapest alternatives. However, without a gas, convection is not possible and heat can be mainly evacuated via conduction in the contacts. This reduces its viability in HV, where the high currents circulating

through the breaker in normal operation will heat the contacts excessively. As seen in Figure 2-5, it has a lower limit than SF6 devices.

Although there are vacuum breakers available for HV, it is a challenge to make them technically and economically viable, and it has not been achieved over 145 kV [18].

### 3.1.6 Equipment developed

Since the introduction of C4-FN by 3M™ [18], some industries have made a push for this compound as their SF6-free alternative. General Electric has installed over three hundred bays of g3 145 kV GIS at over forty sites and eighteen bays in two sites at the level of 420 kV. They have also installed more than 10,000 meters of 420 kV GIL and a hundred 123 kV live-tank circuit breakers [62]. At the time of their publication, their portfolio included GIS up to 420 kV and circuit breakers up to 145 kV. By 2026, it will include circuit breakers, both dead-tank and live-tank, up to 550 kV [62].

The different composition and fluid mechanics of the gas compared to SF6 make necessary small changes from the usual equipment. Kieffel et al., [18] mentions technical upgrades to "sealings, absorbers, monitoring devices and filling valves". Different materials for sealings is necessary on two accounts: first, the different fluid dynamics can lead to higher leakage rate. Second, the sealing may interact with the new compound or its byproducts under decomposition. The EPDM rubber used for gasket materials with SF6 is replaced with halogenated butyl rubber [45], for example.

Other companies have also invested in this compound, such as Hitachi Energy in their GIS line EconiQ™. There are currently two devices in this line: the ELK-04 for 145 kV, and the ELK-03 for 420 kV [31]. Their ratings are the same as the SF6 devices discussed in Section 2.2. They use a mixture with the composition, in volume shares, 3.5% C4-FN / 86.5% CO2 / 10% O2 [12].

Hitachi Energy has also published their Life Cycle Analysis of the technology [12] under ISO 14040 [11]. This analysis includes a list of modifications necessary from the usual equipment:

- An increase of pressure from 6 to 8.8 bar to account for lower dielectric strength.
- Either an increase of wall thickness (not specified), or a change of manufacturing process from sand cast to dye cast to account for the higher pressure.
- An increase of pressure for the circuit breaker, from 7 to 8.8 bar. Its height has to be increased 300 mm for additional exhaust volume.
- Higher stored energy in drive for faster interrupter.
- New mechanism to increase the speed of disconnectors and earth switches. It does not result in significant material increase.

Table 3-6 Comparison of GIS from Hitachi Energy: SF6 - g3. Source: [31]

| Characteristic              | SF6 Switchgear: ELK-04 | Eco Switchgear: ELK-04-ECO           |
|-----------------------------|------------------------|--------------------------------------|
| Rated voltage               | 145 kV                 | 145 kV                               |
| Rated current               | 3.15 kA                | 3.15 kA                              |
| Rated short-circuit current | 40 kA                  | 40 kA                                |
| Insulation                  | SF6                    | 3.5% C4-FN / 86.5% CO2 / 10% O2 [12] |
| Pressure                    | 6 bar [12]             | 8.8 bar [12]                         |
| CB Pressure                 | 7 bar [12]             | 8.8 bar [12]                         |

The changes are small, and the volume remains the same as the SF6 models, except for the circuit breaker. These modifications increase the amount of materials needed. Overall they increase by 12%, from 3,279.5 kg to 3,675.6 kg, mostly accounted by aluminum [12]. This results in a higher footprint in manufacturing, transport, and recovery/recycling, but it the significantly lower impact of emissions during its operation lead to a lower impact on its whole life cycle. They are shown in Table 3-7.

Table 3-7 Comparison of emissions of GIS from Hitachi Energy. Source: [12]

| Equipment                        | Manufacturing | Transport | Gas leakage | End-of-life |
|----------------------------------|---------------|-----------|-------------|-------------|
| SF6 (ELK-04 145 kV) [kg CO2 eq.] | 24,127        | 602       | 96,632      | 5,130       |
| g <sup>3</sup> [kg CO2 eq.]      | 28,142        | 670       | 1,251       | 5,427       |
| Technical Air [kg CO2 eq.]       | 36,936        | 826       | 0           | 6,266       |

Air and CO2 GIS have been developed for HV up to 145 kV, such as the Siemens Blue GIS™ line [32]. While CO2 can potentially be used in interruption at this level, the equipment designed uses vacuum instead. It has a higher overall volume and weights 33% more than its SF6 counterpart.

Table 3-8 Comparison of GIS from Siemens: SF6 - Air. Source: [32]

| Characteristic              | SF6 Switchgear: 8DN8  | Air Switchgear: 8VN1 |
|-----------------------------|-----------------------|----------------------|
| Rated voltage               | 145 kV                | 145 kV               |
| Rated short-circuit current | 40 kA                 | 40 kA                |
| Interruption                | SF6, self-compression | Vacuum               |
| Insulation                  | SF6                   | Clean air            |
| Size                        | 2600x4100x1200 mm     | 3200x5500x1000 mm    |
| Weight                      | 4.5 tons              | 6 tons               |
| Pressure                    | -                     | 8 bar                |

Hitachi's LCA [12] also studies technical air as a possibility. Although their results do not apply to Siemens Blue line process, they give a detailed idea of its status and feasibility in the industry. Its bigger size and weight increase significantly the impact on the manufacturing, transport and recovery/recycling phases compared to both SF6 and g3 devices, but it has no impact during operation, as seen in Table 3.7. Considering its whole cycle, it has significantly lower impact than SF6 devices, as expected, but slightly higher than g3 ones.

### 3.1.7 Conclusions from the researchers

The properties required for the GIS present many negative synergies: bigger molecular size increases the dielectric strength, but also the boiling point, radiative efficiency impacts positively both the dielectric strength and the GWP, an inert nature helps avoid decomposition in flash-over events, but increases the lifetime in the atmosphere, etc. [45].

SF<sub>6</sub>'s unique combination of properties at that level of performance has not been found in any other single gas. All of the studies consulted agree that there is not one compound that can completely substitute it. Rabie et al., sentence in their assessment that "Neither experimental nor computational systematic searches for direct SF<sub>6</sub> replacements in electrical equipment found compounds than can be used as pure gases and no compound stands out above all the others in being the ideal gas that is superior with respect to all requirements" [45].

Instead, research focuses on mixtures of gases and promotes the use of different alternatives in different applications. They also agree on the fact that research is still on going and there are many aspects that need to be studied more in-depth. Tian et al., close their final remarks saying that "There are still many unexplored areas for the gas currently studied. (...) Research on alternative gases still faces greater challenges and requires significant time and economic investment" [22].

On a technical level, the alternatives for insulation are more developed, but "the interruption medium needs further exploration" [22].

Medium Voltage level poses less challenges. The lower insulation requirements allow to operate at lower pressures, which reduces complexity of physical design, manufacturing footprint and reduces the boiling point. The use of air as an insulating medium or vacuum in circuit breaking has been in use for many years. New alternatives such as HFO1234zeE and C5-FK are being studied, but need more time and development.

In High Voltage level the negative synergies between properties are more noticeable. Below 145 kV, the situation is easier, and equipment based on air and vacuum already exists [32], but EHV is more challenging. While the fluorine C4-FN proves an interesting option, there is some emphasis in the academy on the need of further study of its decomposition.

Li et al., remarked in 2018 that one of the challenges was "(...) whether these gases [C5-FK and C4-FN] can be used for GCBs, mainly because of the toxicity of the by-products when an electrical arc occurs" [63] and that "more systematic and detailed investigations on the products of dissociation under different discharge conditions should be carried out" [63]. Two years later, Tian et al., still put emphasis on this topic [22].

In contrast, this gas has seen a big push in industrial applications and it is already in use. General Electric has made a big push, installing it in over forty sites around the world [62]. Hitachi Energy has also invested in it, and there are currently available GIS up to 420 kV [31]. This would put these technologies at a TRL 8 or 9, as the system is proven against industrial norms and the manufacturing is being optimized. Air is also used, by the devices are bigger and heavier, and crossing the 145 kV level poses a bigger challenge.

### 3.2 ADVANCE METHODS AND MACHINE LEARNING

The challenge of the replacement of SF<sub>6</sub> not only lies on the alternatives available, but in how to introduced them. For this, the monitoring methods are a key

resource. Machine learning tools can help even further by using the data gathered by the sensors to make actual decisions.

The critical importance of these devices in the power system and the danger of the leakage in case of a major malfunction has made their monitoring a hot topic in state of the art research, resulting in more advance methods to detect leakage, faults or to estimate RUL that involve not only the sensors, but new emerging technologies such as Machine Learning (ML).

This section introduces some of the relevant research directions currently understudy, giving background information, discussing how machine learning is applied and how it has progressed during the last decade.

### 3.2.1 Leakage detection.

The use of ML for early detection of leakage has seen success in studies such as the one carried by Kaur and Choudhury (2016) [30]. They propose the use of multiple sensing points (four, in their study), to eliminate the effect of difference in the density profile in the gas as a local measurement, and feed the pressure distribution to a classifier to pinpoint the leakage.

The study compares two algorithms: support vector machine (SVM), a more traditional classifier, and multilayer perceptron network (MLP), a more advanced classifier based on neural networks. The MLP has higher accuracy, 78.3% compared to 50.5% of the SVM [30]. This method reduces the requirement on the sensors, and it directly helps the maintenance operators by giving the direct location of the leakage, reducing testing times of each GIS compartment.

Research on this direction has continued since then. In Sweden, Lindskog, Neandhers and Thiringer (2023) [64] have tested similar systems based purely on pressure measurements on three substations. Their algorithm is able to detect leakage on the order of 0.1%/year (the limit set on European regulations) within three weeks. The system has a reported cost installation of 750€ per sensor.

This method could work very well for the replacement plan and add to the project. It can show tendencies on the leakage rate of specific devices, as it usually increases over time with wear and tear, something not considered in this project. This information could be used in the decision to replace a switchgear before the end of its lifetime, comparing the baseline case with the early replacement simulation.

For example, if we look at a device that has 5 years left, and it has a leakage rate of 0.1% per year, assuming 63 kg of SF<sub>6</sub> of content, it will emit 7,402.5 kg of CO<sub>2</sub>eq. until the end. Since this is less than the manufacturing footprint of a new C4FN device, it can be assessed that it should not be replaced. But if it has triggered the classifier, and in maintenance it is discovered that it has had more wear and tear and has instead a 0.5% leakage rate, it will now emit 37,012.5 kg CO<sub>2</sub>eq. In this case, installing a new device would reduce emissions in those five years. Having more accurate information from machine learning methods can help make these decisions.

This also synergizes with the assessment model proposed in this project, as leakage rate is an input parameter. Using the data from the classifier would bring the model from a top down view to a per device view, and give more accurate results for the baseline scenario.

### 3.2.2 Decomposition component analysis.

The decomposition component analysis is used in the detection of arcing phenomena, partial discharges and full breakdowns. It looks for the presence of gases formed in the decomposition of SF<sub>6</sub> at high temperature. Which gases are present and at what concentration is an indicator of the energy of the arcing and, therefore, type and degree of fault. Figure 3-3 shows the concentration of three gases used in fault identification (SO<sub>2</sub>, SOF<sub>2</sub> and CO<sub>2</sub>, see Table 3-9) depending on the temperature.

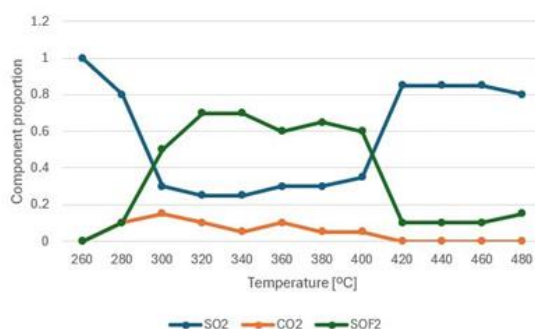


Figure 3-3 Proportion of decomposition components depending on fault temperature. Source: own version, data from [26]

Table 3-9 Boundaries of component concentration for each type of fault [26]

| Fault                      | %c(SOF <sub>2</sub> +SO <sub>2</sub> ) | %c(9SO <sub>2</sub> F <sub>2</sub> ) | %c(5CO <sub>2</sub> ) |
|----------------------------|----------------------------------------|--------------------------------------|-----------------------|
| Partial discharge          | 19.80 - 100                            | 0 - 33.30                            | -                     |
| Partial over-thermal fault | -                                      | 33.30 - 100                          | 0 - 46.90             |
| Spark discharge            | 0 - 19.80                              | -                                    | 46.90 - 100           |

This assessment method is postulated against others such as pulse current or UHF because it can do online monitoring (not requiring pauses in operation), it is quantitative (it can give the degree of the fault) and can detect thermal faults. The method is enhanced with the use of different machine learning methods, such as coding trees, decision trees, and computer recognition algorithms [26].

Zeng et al., summarize the history of this method in their article *SF<sub>6</sub> decomposition and insulation condition monitoring of GIE: A review* (2021) [26].

In their study, they find three main components to classify faults: the concentrations of SOF<sub>2</sub>+SO<sub>2</sub>, 9SO<sub>2</sub>F<sub>2</sub>, and 5CO<sub>2</sub>. Using fuzzy C-means clustering, a ML classifier algorithm, they obtain the definitions for each type of fault shown in Table 3-9 on a triangular diagram. The precision is 128 correct classifications out of 150 experimental samples [26].

This method has already been implemented in China with success across 63 different substations. Thanks to it 55 latent problems on SF<sub>6</sub> equipment have been detected [26].

However, this method is not considered appropriate for the replacement phase. Although they are very important to better detect the type of arcing, in this project what's being evaluated is tools to transition towards new alternatives. As the g3 gas does not share the decomposition mechanisms and products of SF6, the investment done in this direction would not be useful after the transition. It can also be more expensive, as the sensors used are not included by the manufacturer.

### 3.2.3 RUL estimation.

Estimating the RUL using the number of operations, as described in the beginning of the section, is a very simple method that can be easily done by a counter on the switches such as the one in the Sensgear™ in Siemens devices. However, the reference is a different device in a laboratory environment using only external factors (number of cycles) that do not reflect the actual state of the machine. This method tends to underestimate the RUL, as it does not consider arcs of lower energy that have less toll on the contacts [65].

Bagherpoor, Rahimi, Razi-Kazemi, and Niayesh (2016) [65] proposes a more precise method using the accumulated energy of the arc. The energy can be obtained from the power, that is, from the product of voltage and current during the arcing, as in Equation 3.1. The RUL is then calculated using Equation 3.2. This method requires a more complex set-up, capable of measuring the transient voltage and eliminate the noise from electromagnetic effects.

$$E = \int_0^{t_{arc}} u(t) \cdot i(t) \cdot dt \quad (3.1)$$

Where  $E$  is energy,  $t_{arc}$  is the time of the arcing,  $u(t)$  is the arc voltage over time, and  $i(t)$  is the arc current over time.

$$RUL = \left[ 1 - \frac{\sum E_i}{AE} \right] \cdot TL \quad (3.2)$$

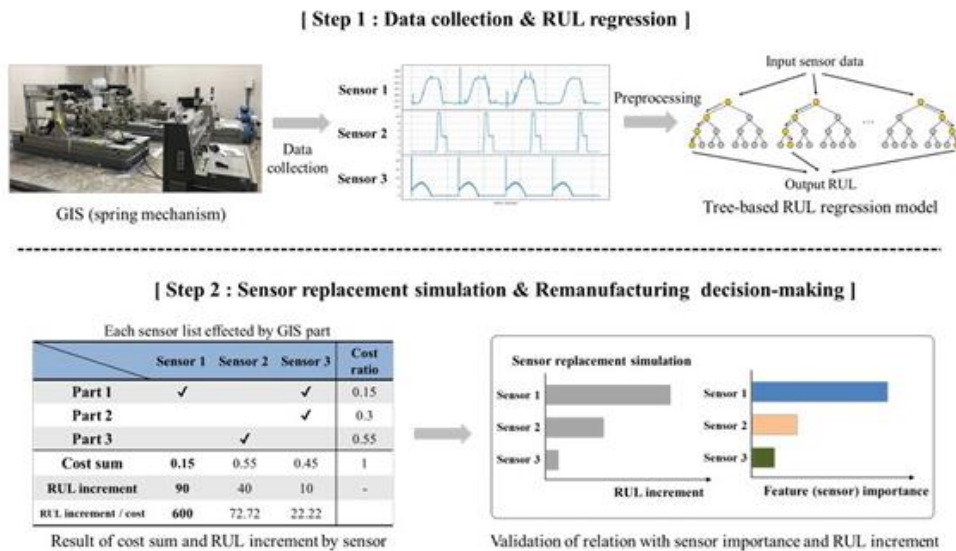
Where  $RUL$  is the Remaining Useful Life,  $E_i$  is the energy of one arcing event,  $AE$  is the rated accumulated energy, and  $TL$  is the Total Lifetime.

The estimation is improved considerably. Test 1 of their study has a RUL of 98.23%. The conventional method underestimates it to 95%, whereas this calculation improves the estimation to 98.13% [65]. The effect is more noticeable the longer the lifetime; in their Test 6, with an actual RUL of 82%, the conventional method has accumulated a significant error and estimates 70%, whereas the energy calculation estimates 80.63% [65].

This line of study has continued since then, with multiple citations in the last five years.

In a different direction, it is especially interesting the study done by Moon et al., (2022) [38]. With a perspective of remanufacturing, a more sustainable approach to maintenance and manufacturing through the reuse of functioning components, it

uses a tree-based RUL regression model to make economical decisions about the device.



**Figure 3-4 Process for remanufacturing decision making using RUL regression models.** Source: [38] under CC BY license (<https://creativecommons.org/licenses/by/4.0>)

This is a two step process, as seen in Figure 3-4. First, a regression model for the RUL is built using the data form sensors in critical components during an accelerated life study of the switchgear.

In the study, they compare the results between six different machine learning algorithms: linear regression, Ridge, least absolute shrinkage and selection operation (LASSO), Elastic Net, Random Forest and extreme gradient boost. Random Forest gives the best model with an  $R^2$  of 0.999, a Mean Squared Error (MSE) of 0.463 and a Mean Absolute Error (MAE) of 0.263 [38].

With the model, in the second step for each sensor the impact on RUL by its correspondent component is calculated. Knowing the price of repairing or replacing that component, the increase of RUL per unit of cost invested can be defined. This gives more detailed and accurate information in the economical decision making. Their results shows that the motor current sensor in the switch is the most cost effective [38]. However, the study is limited in the number of devices used to create the model in the first step.

This approach is the most interesting for the replacement. This work could be expanded to also include environmental factors, such as % RUL increased by kg of CO<sub>2</sub> eq. emitted, covering both Eco-Eco factors.

The method would serve two functions. First, a better estimation of RUL could substitute the static value of the devices' lifetime used on our simulation. Then, these two indicators could be compared to the alternative of replacing the device with one of the new technologies, and make the appropriate decision case by case. This is, however, a more expensive option, as it requires an Accelerated Life Study.

### 3.3 CONCLUSIONS

For their higher Technology Readiness Level, g3 (NOVEC™ 4710 or C4FN mixtures) and Air were seen as the most viable alternatives. Both have devices that have been tested by professional manufacturers and seen operation in actual substations. g3 has an advantage in performance, but has a higher GWP. Air has no operation emissions and is more readily available as a gas, but it has worse performance and higher costs in manufacturing. These two are the technologies considered in the simulations in this project.

Although outside of the scope, some conclusions can be done for the other devices:

- MV switchgears: at the MV level there are already many traditional alternatives available. If size is a limiting factor so that air cannot be used, PFKs have seen good performance at this level and have lower GWP than C4FN.
- Instrument transformers: without the need for current interruption, air is a good alternative. C4FN can be used at higher voltages.
- GIL: there are already g3 GIL in use [62].

The use of machine learning tools can help the transition towards new alternatives. The simulations done in this project (see later Chapter 5) had a top view perspective, using aggregated data on the system as a whole. The machine learning tools just discussed, on the other hand, study one individual device. However, if the work is expanded by specific companies with direct access to their devices and more detailed data, it offers some good opportunities.

ML algorithms on leakage detection using pressure/density sensors are promising. They can both synergize with the assessment model in this project giving more accurate leakage rate measurements and help detect equipment with wore-down sealings that need early replacement. Practical and cheap set ups have already been studied in Sweden [64]. Furthermore, they are easily translated to g3 alternatives as the pressure conditions are similar.

Advance methods of RUL evaluation with ML models can help evaluate the economical impact of replacing compared to repairing, and thus help make decisions during the transition. However, this method is more expensive as it need an ALS to train the model.

## 4 Methodology and methods

This project wanted to answer three questions:

1. **How can the phase out be handled in an efficient and rational way? Do we need to replace all components directly, or can we change them in a more need-driven approach?**
2. **What equipment should we use instead of the one containing SF6? What is most cost-effective and best from an environmental point of view for each application?**
3. **How can replacement need be detected? Can cheap sensor-systems do this? Can the implementation of machine learning help?**

Whereas questions n° 2 and 3 have been answered through the literature review of the state of the art (Chapter 2 and 3), question n° 1 requires an empirical analysis.

In this chapter, the methods of this analysis are presented and explained in detail. Section 4.1 gives an overall view of the methods step by step, whereas Sections 4.2 to 4.6 delve into the specific considerations, methods and equations used. It discusses the practical aspects of the methods. The motivations and justifications behind the methodology were presented earlier, in Section 1.7.

### 4.1 RESEARCH PROCESS, PARADIGM AND TOOLS

The objective was to estimate and compare the CO<sub>2</sub> emissions and costs of each replacement plan. This was done with a statistical analysis of the impact of each plan in the time span between 2020 and 2050.

It is a three step method:

1. First, the need of SF<sub>6</sub> in the future is projected based on its relation with the Installed Generation Capacity.
2. Then, emissions and costs are calculated for each replacement plan based on a model, a system of equations, iterating with different input values of the probabilistic variables.
3. Finally, the mean of the objective variables are calculated and compared for statistical significance using statistical analysis tools.

The reason for using statistical analysis is that certain parameters, such as the leakage rate, are not determined but are, instead, probabilistic. Depending on external factors such as differences on manufacturing or maintenance, two machines can present different leakage values, or the value for one machine in two different points of its lifetime might change.

The hypothesis of the experiment is that at least one of the replacement plans has significantly different CO<sub>2</sub> emissions and costs than the rest.

$$\begin{cases} H_o : \mu_{1,j} = \mu_{2,j} = \dots = \mu_{k,j} \\ H_1 : \text{At least one } \mu_{i,j} \text{ is different} \end{cases} \quad (4.1)$$

Where  $H_o$  is the null hypothesis,  $H_1$  is a hypothesis, and  $\mu_{ij}$  is the mean value for the case “i” and the independent variable “j” (CO2 emissions or costs).

The research process can be described, step by step, as follows:

1. Parameters and historical data are recovered.
2. A relation between SF6 stock and Installed Capacity is defined through linear regression (this is validated in [17]).
3. SF6 stock from 2020 to 2050 is calculated using the relation defined in the previous step and the scenarios defined by Svenska Kraftnät for future Installed Capacity.
4. A set of input parameters are obtained as random numbers from their Probability Distribution Function.
5. CO2 emissions and costs for each replacement plan are calculated based on future SF6 stock needs, the parameters and the historical data.
6. Steps 4 and 5 are repeated 200 times for each replacement plan.
7. The results are submitted to an ANOVA to confirm that at least one replacement plan gives significantly different results.
8. The means of the replacement plans are compared by pairs using Student’s t-distribution to confirm that they are significantly different.
9. The validity of the model’s assumptions is evaluated (normality, homocedasticity and independence).
10. If the assumptions are not valid, a transformation is done to the data, and steps 7, 8 and 9 are repeated.
11. The impact of the parameters’ values is evaluated in a sensitivity analysis.

This simulation and analysis is done by code in Matlab, for my familiarity with the program and ease for plotting the results in the software.

## 4.2 HISTORICAL DATA AND PARAMETERS

The rigor of the parameters is extremely important to assure the external validity of the results.

The Historical data was obtained from official sources. Specifically, the Installed Capacity of Sweden was obtained from Eurostats [66], and the SF6 stock from the National Inventory Report [4] and Swedenergi report [3].

The expected value of the leakage rates was obtained from manufacturers, as present in the equipment brochure. These rates are modeled as a PERT PDF, taking the pessimist and optimist values from Billen et al., (2020) [13].

A PERT is a transformation of the beta distribution. It is defined with three parameters, the expected value, the pessimist value, and the optimist value. The mean is calculated as the weighted average of these values, as seen in Equation 4.2. It is widely used in project manage for its transparency: the parameters have a direct and simple translation to the requirements and risks of the project.

$$\mu = \frac{a + 4b + c}{6} \quad (4.2)$$

Where  $\mu$  is the mean,  $a$  is the optimistic value,  $b$  is the expected value, and  $c$  is the pessimistic value.

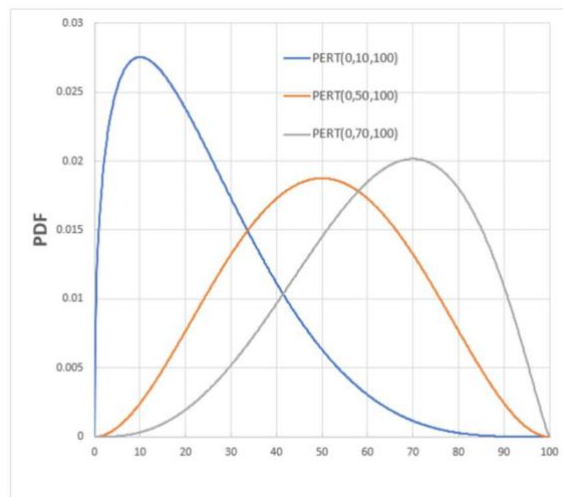


Figure 4-1 Examples of PERT distributions. Source: David Vose CC BY-SA 4.0 (<https://creativecommons.org/licenses/by-sa/4.0>)

The GWP of the different solutions are known values from their chemical properties, and were obtained from the IPCC [2] and Hitachi's LCA [12]. The manufacturing footprint and gas mixture concentrations were also taken from the latter source.

Finally, the future scenarios were taken from Svenska Kraftnät's Market Analysis of 2050 [15].

#### 4.3 SIMULATION DESIGN AND PLANNED MEASUREMENTS

There are four scenarios, three technologies and five plans (one persistence case, and four replacement plans) for a total of twenty eight cases that have to be simulated. Each case is composed of:

- Independent variables: replacement plan.
- Background conditions: scenario, parameters, PDFs.

- Dependent variables: CO2 emissions, costs.

Replacement plans must be compared against each other under the same conditions in order to obtain results that are internally valid. Therefore, each scenario is evaluated independently of the others, which results in four groups of seven cases.

#### **Persistence case.**

The persistence case serves as a baseline with which to compare the results of each replacement plan. The independent factor with which the scenarios are being influenced is the change of technology. Therefore, for each scenario, the persistence case consists of not replacing SF6 during the whole cycle (2020-2050), and calculating the emissions and costs that result for continuing this technology.

**The scenarios**, as defined in Svenska Krafnät's report [15], are:

- *Småskaligt förnybart (SF)*, small-scale introduction of renewables: this scenario has the least growth of energy demand by 2050, and slowly introduces renewable sources to substitute nuclear energy.
- *Färdplaner mixat (FM)*, mixed plan: this scenario has a moderate growth of energy demand, and utilizes both renewables and nuclear sources.
- *Elektrifiering planerbar (EP)*, sharp electrification: this scenario experiments a big growth of energy demand, and proceeds with a big electrification of the system using both renewable and nuclear solutions.
- *Elektrifiering förnybart (EF)*, sharp electrification using renewables: this scenario also has a sharp growth of energy demand, and covers it exclusively with renewable sources, eliminating nuclear energy.

**The three technologies** are the current solutions being developed by companies such as Hitachi Energy, Siemens and General Electric:

- SF6: considered for the persistence case as a baseline.
- C4-FN mixture with CO2.
- Air.

**The five plans** are:

- Business as usual: the persistence case, this plan continues the use of SF6.
- Hard plan: all the installed SF6 is replaced at the start of the timespan.
- Standard plan: replacement as needed, this case replaces the devices that have reached the end of its lifetime.
- Delayed plan: this case starts replacing SF6 in 2030, and from that year continues with a "replacement as needed" approach.
- Half-life plan: replacement as needed, but the SF6 equipment is replaced when reaching half of its lifetime, instead of at the end of it.

### Emissions model.

To calculate the objective variables, the following model was implemented. This model is based on the work of Billen et al., (2020), but adding the economic factors and adapting some calculations in the code for the idiosyncrasies of each plan which were not considered in the reference study.

First, a functional unit for the calculations must be defined. This functional unit is the basic equipment that composes the power system, and the costs or number of units installed are based around it. The details of the functional unit are explained in Chapter 5.

Future stock need of SF6 is calculated using the function obtained from the linear regression.

$$SF6_{stock}^t = a \cdot IC^t + b \quad (4.3)$$

Where  $SF6_{stock}^t$  is the stock of SF6 in the system in the year “t” (from 2020 to 2050),  $IC$  is the Installed Capacity in the generation system,  $a$  and  $b$  are parameters from the linear regression between SF6 stock and installed capacity.

Then the stock growth of each gas is calculated based on the need obtained previously. This does not considered decommissioned devices, which are included later.

$$SG_g^t = HV_{share} \cdot (SF6_{stock}^t - SF6_{stock}^{t-1}) \cdot RF_g \cdot PO_g^t \quad (4.4)$$

Where  $SG_{stock}^t$  is the growth of the stock of the gas “g” in the year “t”,  $HV_{share}$  is the proportion of stock used in HV compared to all of the system,  $RF_g$  is the replacement factor for the gas “g” and  $PO_g^t$  is a binary indicator of use of gas “g” in the year “t”.

In the alternative technologies SF6 is not replaced by a pure gas, but by a mixture of gases. The Replacement Factor  $RF_g$  represents the proportions of the mixture. A binary indicator,  $PO_g^t$ , indicates if the gas “g” is in use in that given year. Thus, for SF6  $PO_{SF6}^t$  is 1 in the persistence case, and 0 in the rest.

Then the stock from the decommissioned devices is calculated, that is, those that have reached the end of their lifetime. If  $LS$  is the lifetime in years, the stock decommissioned is the Stock Growth of  $LS$  years ago. This information is available in the NIR [4] from 1990 onwards.

$$SD_g^t = SG_g^{t-LS} \quad (4.5)$$

Where  $SD_g^t$  is the amount of gas “g” that is decommissioned in year “t”, and  $LS$  is the lifetime of the device in years.

This decommissioned gas is subtracted from the stock growth for SF6 (except in the persistence case, where SF6 is continued, and the delayed case before 2030), and summed for the alternative technologies, to obtain the net stock growth.

$$\begin{cases} NSG_{SF6}^t = SG_{SF6}^t + SD_{SF6}^t \cdot (2 \cdot PO_{SF6}^t - 1) \\ NSG_{other}^t = SG_{other}^t + SD_{SF6}^t \cdot RF_g \cdot PO_{other}^t \end{cases} \quad (4.6)$$

Where  $NSG_g^t$  is the Net Stock Growth of gas “g” in the year “t”, accounting for both the growth of the system and the replacement of the decommissioned gas.

From these values, and the definition of the functional unit, the number of units that must be installed can be calculated.

$$FU^t = \frac{HV_{share} \cdot (SF6_{stock}^t - SF6_{stock}^{t-1})}{GB_{SF6}} \quad (4.7)$$

Where  $FU^t$  is the number of functional units installed in the year “t”, and  $GB_{SF6}$  is the amount of SF6 in one functional unit.

With the stocks of each gas every year, the emissions can be calculated using the leakage rate parameters. To study the whole life cycle of the device, manufacturing, operation and decommission must be included. Manufacturing footprint is taken from Hitachi’s LCA [12], but the other two must be calculated.

Manufacturing:

$$EM_g^t = MF_g \cdot FU^t \quad (4.8)$$

Where  $EM_g^t$  is the emissions from manufacturing of gas “g” in the year “t”, and  $MF_g$  is the manufacturing footprint of one functional unit that uses gas “g”.

Operation emissions:

$$EO_g^t = GWP_g \cdot EOF_g \cdot S_g^t \quad (4.9)$$

Where  $EO_g^t$  is the emissions from operation of gas “g” in year “t”,  $GWP_g$  is the Global Warming Potential of gas “g”,  $EOF_g$  is the leakage rate of gas “g”, and  $S_g^t$  is the stock of gas “g” in the year “t”.

Decommission emissions:

$$ED_g^t = GWP_g \cdot EDF_g \cdot SD_g^t \quad (4.10)$$

Where  $ED_g^t$  is the emissions from decommission of gas “g” in year “t”,  $EDF_g$  is the leakage rate of gas “g” during dismantling of the unit, and  $SD_g^t$  is the stock decommissioned of gas “g” in the year “t”.

And finally, the carbon footprint of the whole LCA can be obtained from the sum of the different parts.

$$CF^t = \sum_g (EM_g^t + EO_g^t + ED_g^t) \quad (4.11)$$

In regards of costs, the investment cost is calculated in per units, that is, with the investment cost of the functional unit as the base. The value of the money is updated to the current year considering the interest rate.

$$C^t = \sum_g \frac{IC_g}{(1+r)^{t-1}} \cdot FU_g^t \quad (4.12)$$

Where  $C^t$  is the installation cost in the year “t” updated to the current year,  $IC_g$  is the installation cost of one functional unit of gas “g”, and  $r$  is the interest rate.

#### 4.4 STATISTICAL ANALYSIS PROCESS

From the simulation of each scenario, seven sets of emissions and costs are obtained. In order to discuss which of the plans yields better results, the mean value of each is compared to the rest. A statistical analysis tell us if the difference between means is significant with a specific level of confidence.

The hypothesis (Equation 4.1) is that at least one mean is significantly different.

The result obtain in the calculations,  $y_{ij}$ , with  $K$  plans and  $n_i$  simulations per plan, can be expressed as the sum of a predictable component,  $\mu_i$ , and an unexplained/random component,  $u_{ij}$ . It is assumed that the random component follows a normal distribution.

$$y_{ij} = \mu_i + u_{ij} \quad u_{ij} \rightarrow N(0, \sigma^2) \quad (4.13)$$

Since more than two plans are being compared against each other, the appropriate method is an ANOVA. This method studies the variance of the results by dividing in two components: the explained variance,  $VE$ , (Equation 4.14) and the unexplained variance,  $VNE$ . The variances are then compared against a F-distribution for a given confidence level (Figure 4-2) to determine if the hypothesis, “at least one mean is different”, is true. This method is visualized in an ANOVA table, which is directly computed by the code.

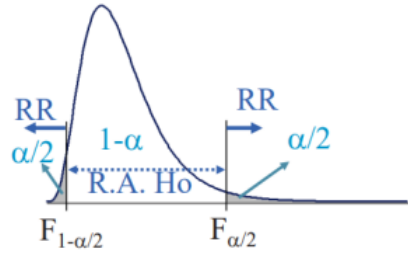
$$VE = \sum_{i=1}^K n_i \cdot (\bar{y}_i - \bar{y}_{..})^2 \quad (4.14)$$

$$VNE = \sum_{i=1}^K \sum_{j=1}^{n_i} e_{ij}^2 = \sum_{i=1}^K \sum_{j=1}^{n_i} (y_{ij} - \bar{y}_i)^2 \quad (4.15)$$

$$VT = VE + VNE \quad (4.16)$$

Table 4-1 Theoretical ANOVA table

| Source   | Sum of squares | Degrees of Freedom | Variances     | F                                    |
|----------|----------------|--------------------|---------------|--------------------------------------|
| Plans    | VE             | K-1                | VE/(K-1)      | $\frac{VE}{(K-1) \cdot \hat{s}_R^2}$ |
| Residues | VNE            | n-K                | $\hat{s}_R^2$ |                                      |
| Total    | VT             | n-1                |               |                                      |


Figure 4-2 Contrast with F-distribution for a given  $\alpha$  confidence level. RR denotes Rejection Region

If from the previous analysis the plans are shown to yield significantly different results, the plans can be contrasted in pairs using Student's t-distribution. Given the following hypothesis:

$$\begin{cases} H_o : \mu_i = \mu_j \\ H_1 : \mu_i \neq \mu_j \end{cases} \quad (4.17)$$

The value of the difference in t-distribution can be calculated as in Equation 4.18, and then compared with the Acceptance Region for a given confidence level  $\alpha$ , as in Figure 4.3.

$$t_{ij} = \frac{\bar{y}_i - \bar{y}_j}{\hat{s}_R \cdot \sqrt{\frac{1}{n_i} + \frac{1}{n_j}}} \rightarrow t_{n-K} \quad (4.18)$$

Where  $t_{ij}$  is the difference factor,  $\bar{y}_i$  is the mean value of plan "i" from the simulations,  $\hat{s}_R$  is the standard deviation,  $n_i$  is the number of samples of plan "i", and  $t_{n-K}$  is the Student's t-distribution for n-K degrees of freedom.

The mean value that have been compared in the analysis are not the predictable component of the model, but simply an estimation of it. The confidence range of the predictable component,  $\mu_i$ , can be defined with Student's t-distribution (for a given confidence level  $\alpha$ ) as seen in Equation 4.19.

$$\mu_i \in \bar{y}_i \pm t_{\alpha/2} \frac{\hat{s}_R}{\sqrt{n_i}} \quad (4.19)$$

Where  $t_{\alpha/2}$  is the value of confidence level  $\alpha$  in Student's t-distribution.

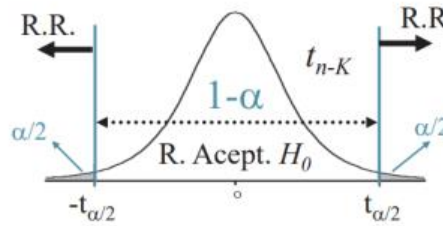


Figure 4-3 Contrast with Student's t-distribution for a given  $\alpha$  confidence level. RR denotes Rejection Region

The results will be compared against a confidence level of  $\alpha = 0.05$ , a standard value in this kind of analysis.

#### 4.5 VALIDATION OF THE MODEL

The model used in an ANOVA (Equation 4.13) follows three assumptions:

- Normality: the model follows a normal distribution,

$$y_{ij} \rightarrow N(\mu_i, \sigma^2)$$

- Homocedasticity: the deviation is the same for every set of samples,

$$Var[y_{ij}] = \sigma$$

- Independence: the set of observations are independent of each other,

$$Cov[y_{ij}, y_{kl}] = 0$$

These assumptions must be verified to validate the results from the ANOVA.

The normality can be verified visually with a Q-Q plot. This plot shows the residuals,  $e_{ij}$ , against the percentile in a normal distribution. If the residuals follow a normal distribution, the plot is linear. Examples of Q-Q plots can be seen in Figure 4-4.

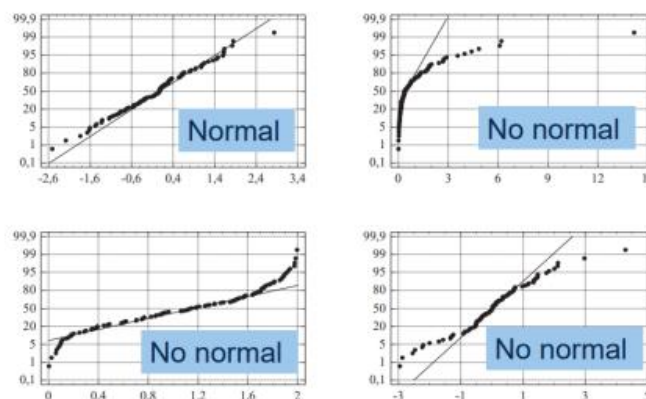


Figure 4-4 Examples of Q-Q plots that show normality and non-normality

Homocedasticity can also be verified visually plotting the dispersion of the residuals, as seen in Figure 4-5. If the maximum dispersion is less than 3 times

bigger than the minimum dispersion, it can be considered that the model is homocedastic.

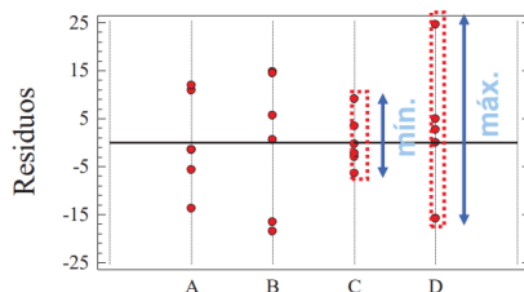


Figure 4-5 Example of dispersion of residuals for four treatments, A-D

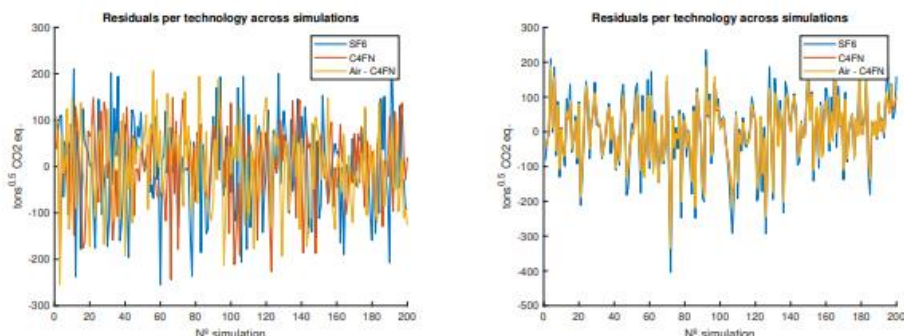
If these assumptions are broken, the data is transformed so that it follows a normal distribution. Two transformations are tested, exponential and logarithmic, and the one that better complies with the assumptions is chosen.

$$\begin{cases} z_{ij} = y_{ij}^p \\ z_{ij} = \log(y_{ij}) \end{cases} \quad (4.20)$$

Independence is assured in the experiment design stage. It is important that the probabilistic component of the parameters is defined randomly for each simulation, in order to avoid dependence and systematic errors.

The error is unknown and cannot be checked to detect dependence, but it is represented by the residuals. These can be used to assess the hypothesis by plotting them across observations (simulations): if any pattern is discernible, there might be influence between observations. The residuals showing a random distribution does not confirm independence (as there could be some relation that is not directly observable), but, along with a good experiment design, can be a sufficient indicator of it.

Figure 4-6 shows a comparison of the residuals when the simulations for each technology are done separately (good experiment design, as it keeps the error from the stochastic parameters independent), and when they are done in the same loop on the code. In the second case it can be easily observed that the residuals for all technologies follow the same pattern, and are, therefore, not independent between each other.



(a) Residuals in Scenario SF. Independent simulations. (b) Residuals in Scenario FM. Dependent simulations.

Figure 4-6 Verification of independence of observations through residual's plots. Examples.

## 4.6 VALIDATION OF THE RESULTS

There are two considerations when evaluating the results: internal validity and external validity.

Internal validity mostly refers to the experiment's design. A scientific study is internally valid if the observed effect is a result of its relation with the factor under study, and not influence of some uncontrolled background factor. This is a bigger problem in live experiments than in simulations. In the case of this project, as the observed effect is the result of a set of equations explicitly stated, and all the background conditions are defined in the computer code without any possible outside influence, the only case of internal invalidity is a typing error when writing the code, which is only a matter of double checking it.

External validity refers to the inference from the observed effect in the experiment to the general population. This is a critical factor of models and simulations. If they do not reflect correctly the reality they are trying to represent, although the observed effect is internally valid, it cannot be extrapolated outside of the simulation data.

It is very hard to detect external invalidity. However, a sensitivity analysis can help understand and quantify the effect of the individual parameters on the observed effect. With this knowledge, if one parameter does not represent reality, the results can be more easily readjusted and still hold value.

In this project, the sensitivity analysis consists on changing the value of one parameter by  $\pm 10\%$ , with the rest of the factors unchanged, and observe the change on the effect. The ratio of the difference over the increase quantifies the sensitivity.

For leakage rates, manufacturing footprint, and costs, observing the effect of a decreasing parameter is less important in this specific project, because it leads to more optimistic scenarios. If the leakage rate of the device decreases by 10%, then there is less emissions. The results of the project for not considering this decrease fall, then, on the conservative side. For lifetime of the equipment it is the opposite.

## 5 Simulation's definition and characteristics

This chapter describes the simulation, covering step by step the data that is being use and how it is use to obtain new data, and defining the functional unit, the parameters and the assumptions of the model.

### 5.1 HISTORICAL DATA AND SCENARIOS

The projections of the emissions and costs in the future was built upon the historical data on SF6 stock, obtained from the NIR [4], and the Installed Capacity, obtained from statistical data from the EU [66]. A portion of this data is shown in Table 5-1, and the full table can be found in Appendix B; it can also be seen in Figure 5-1.

Table 5-1 Extract of historical data for Net Generation Capacity and Stock of SF6 in Sweden between 1990 and 2020. Sources: [4, 66]

| Year | Net Generation Capacity (MW) | Stocks in operating systems (tons) | Amount filled in new manufactured products (tons) |
|------|------------------------------|------------------------------------|---------------------------------------------------|
| 1990 | 31,410                       | 56.78                              | 29.93                                             |
| 1995 | 32,127                       | 69.75                              | 29.79                                             |
| 2000 | 32,714                       | 101.20                             | 44.45                                             |
| 2005 | 32,432                       | 135.64                             | 49.59                                             |
| 2010 | 35,332                       | 183.93                             | 48.11                                             |
| 2015 | 39,683                       | 229.29                             | 70.59                                             |
| 2020 | 42,286                       | 269.57                             | 76.84                                             |

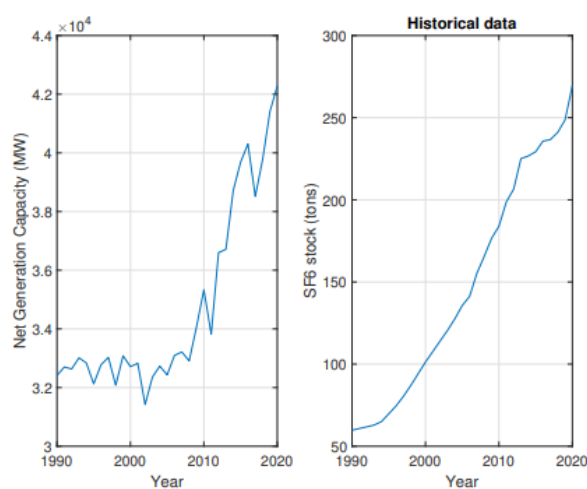


Figure 5-1 Historical data for Net Generation Capacity and Stock of SF6 in Sweden between 1990 and 2020. Source: [4, 66]

Zhou, Teng, and Tong demonstrate in [17] that there exists a linear relationship between the installed capacity of a grid and the amount of SF6. This is because SF6 is associated to the switching devices in substations, the number of which is correlated to the capacity of the system. This relation is also used by Billen et al., in their study of SF6 emissions [13].

The simulation uses this relation to estimate the need for SF<sub>6</sub> in the future, and from there calculate the effect of meeting that need with different technologies. This relation is calculated using Linear Regression in the Matlab Code A.1, line 11, using the built-in function **fitlm**. The linear regression gives the following results:

$$SF6_{stock} \text{ (tons)} = -506.63 + 0.018809 \cdot IC \text{ (MW)} \quad (5.1)$$

Table 5-2 Linear regression between SF<sub>6</sub> stock and Installed Capacity

|                  | Estimate | Standard Error | t-statistic | p-value                |
|------------------|----------|----------------|-------------|------------------------|
| <b>Intercept</b> | -506.63  | 67.63          | -7.4912     | $2.9506 \cdot 10^{-8}$ |
| <b>Slope</b>     | 0.018809 | 0.0019376      | 9.7074      | $1.289 \cdot 10^{-10}$ |

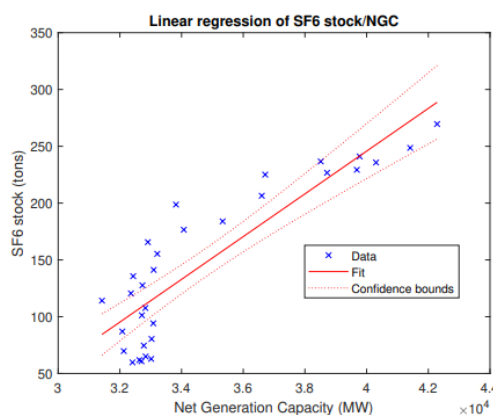


Figure 5-2 Linear regression between SF<sub>6</sub> and Installed Capacity

The fitting has a coefficient of determination  $R^2$  of 0.765. The coefficient is much higher than the estimation used by Billen et al., [13], 0.48. The regression can be considered valid. This difference can be explained as the study by Billen et al., encompasses the whole European system, which involves many countries with different policies on SF<sub>6</sub> monitoring, which can increase considerably the uncertainty of their values, as they discussed in the paper.

Figure 5-2 shows a cluster of data around 33,000 MW that deviates from the linear behavior. This data corresponds mostly to the initial years, 1990- 2000. The values after the year 2000, however, show better fitting to a linear relation. Limiting the regression to the later years (2000-2020) can improve the results, with a  $R^2$  of 0.845, but an argument would need to be made that this is a better representation of the future trend. The project uses the first regression from Table 5-2 with the full historical data.

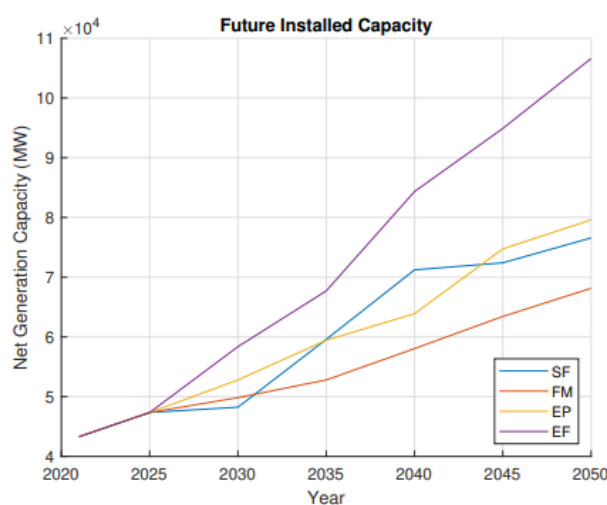
The SF<sub>6</sub> stock is then projected over four future scenarios defined by Svenska Kraftnät in their long-term market analysis [15]. Each of the scenarios covers the time period between 2020 and 2050, with different hypothesis on the demand growth and different strategies on the growth of generation capacity.

Figure 5-3 shows the evolution of each scenario during the years. The specific values are shown in Table 5-3 and Appendix B. As the report was written just before 2020, the data for the year 2020 have been updated with the real known values from Table 5-1. Data for the intermediate years (e.g. 2021-2024) are assumed

to follow linear interpolation, with a set growth in the 5 year span. A summary of each scenario can be found in Appendix C, and in more detail in their original source, [15].

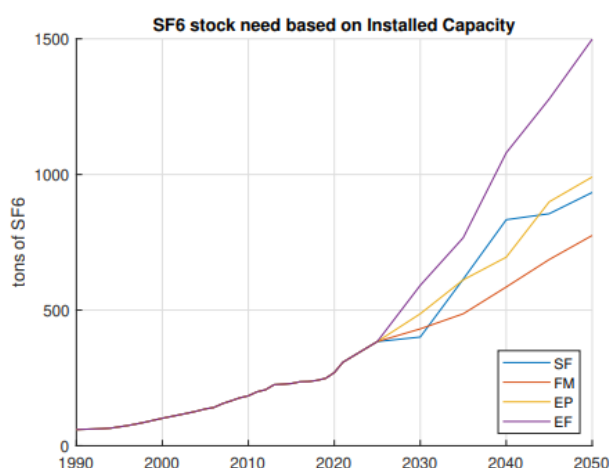
**Table 5-3 Total Generation Capacity of the future scenarios defined by Svenska Kraftnät. Units in MW**

| Year | Småskaligt förnybart | Färdplaner mixat | Elektrifiering planerbart | Elektrifiering förnybart |
|------|----------------------|------------------|---------------------------|--------------------------|
| 2020 | 42,286               | 42,286           | 42,286                    | 42,286                   |
| 2025 | 47,350               | 47,350           | 47,350                    | 47,350                   |
| 2030 | 48,240               | 49,840           | 52,800                    | 58,370                   |
| 2035 | 59,590               | 52,800           | 59,450                    | 67,710                   |
| 2040 | 71,230               | 58,050           | 63,890                    | 84,340                   |
| 2045 | 72,410               | 63,430           | 74,740                    | 94,900                   |
| 2050 | 76,580               | 68,150           | 79,610                    | 106,610                  |



**Figure 5-3 Generation Capacity of the future plans defined by Svenska Kraftnät**

Finally, Figure 5-4 shows the SF6 amount projected in each of the scenarios.



**Figure 5-4 SF6 stock between 1990 and 2050 for the different scenarios**

The amount of SF6 registered in the NIR [4] takes into account all the equipment across all voltage levels, but does not specify amounts per type of equipment. The evaluation in this project focuses on switchgear at HV, where the highest impact has been observed (Section 2.6).

In Billen et al., [13] they approach the estimation of the HV share of SF6 by looking at the share between MV and HV in the five most predominant countries in the system (responsible for 80% of SF6 in the EU): UK, Germany, France, Italy, and Spain. In the case of the first two the share is explicitly reported, whereas for the last three it is estimated from transmission grid data. They find that, on average, the HV share in the European system is 45%.

For Sweden, the data from the NIR [4] can be compared to the data of the report from Swedenergi [3] that focuses on the power grid. This comparison is shown in Table 5-4.

**Table 5-4 SF6 stock comparison between the NIR [4] and the Swedenergi report [3]**

| Year | SF6 stock (tons) in NIR | SF6 stock (tons) in Swedenergi report | Share  |
|------|-------------------------|---------------------------------------|--------|
| 2000 | 101.25                  | 28                                    | 27.65% |
| 2005 | 135.64                  | 77                                    | 56.77% |
| 2010 | 183.93                  | 108                                   | 58.72% |
| 2015 | 229.29                  | 124                                   | 54.08% |
| 2020 | 269.57                  | 153                                   | 56.76% |

On average, the HV share in the Swedish system for SF6 usage is 50.80% with a standard deviation of 13.04%. It is close to the 45% observed by Billen et al., on the European level [13]. However, the sample is very small (data for only 5 years between 2000 and 2020). The HV share is model as a Normal distribution, and the effect of the uncertainty is reduced by doing numerous simulations of the projections in the future.

The equipment under study, switchgears, have a technical lifetime of 40 years, as seen in Section 2.2. As the simulation starts in the year 2020, it would be necessary to know the data from at least 1980. However, as the NIR only reports from 1990 onwards, it is assumed that SF6 started to be installed in 1980, and it grew at a constant rate between 1980 and 1990, calculating it with linear interpolation.

Another important consideration of the historical data is the amount of SF6 added to the system each year. This is the amount that will have to be replaced a number of years later, when the equipment reaches the end of its lifetime. The NIR reports this value for all the equipment, but without specifying to which type of equipment is added.

The value reported presented a problem in the simulation done in this project. Given the long lifetime of the devices, the values reported are too high for this kind of device and using them in the simulation leads to negative stocks.

For example, looking at the transition between 1990 and 1991, the amount in the first year is 59.78 tons of SF6, and 29.93 tons get added in newly manufactured equipment. The amount of SF6 in 1991 rises to 60.79 tons, only 1 more ton even though almost 30 were added, 50% of the total stock. If this was contained in switchgear devices, it would mean that 28 tons were added in 1950 (much earlier than the introduction of this technology, in the 1970s). Then, in 1991 26.1 tons get added, but the stock in 1992 is only 61.81 tons. Every year half the stock gets replaced, which might be logical for other devices with lower lifetimes, but is not realistic for switchgear.

As we assumed that SF6 was implement since 1980, no amount is decompiled between 1980 and 2020, the start of the simulation. The added SF6 amount that was considered in the simulation is calculated as the difference of stock between years.

$$SF6_{new}^t \text{ (tons)} = SF6^{t+1} \text{ (tons)} - SF6^t \text{ (tons)} \quad (5.2)$$

## 5.2 FUNCTIONAL UNIT AND PARAMETERS

The functional unit that serves as a base for the simulations in this project is a 145 kV one-bay GIS. This was chosen because of the information available, as the LCA done by Hitachi Energy [12], the study by Billen et al., [13], and other sources such as the g3 calculator by GE [33], use it as a template.

There are three technologies to consider: SF6, C4FN (g3, or 3M™ Novec™ 4710), and Air with vacuum circuit breakers. For each of these technologies we needed to define a series of parameters for the calculations. Table 5-5, Table 1-1Table 5-6, Table 5-7, and Table 5-8 show these parameters.

Table 5-5 Parameters for SF6 GIS

| Parameter                                     | Value                     |
|-----------------------------------------------|---------------------------|
| GWP                                           | 23,500 CO2 eq. [2]        |
| Amount of gas per f.u.                        | 63 kg [33]                |
| Manufacturing + transport CO2 footprint       | 24,729 kg of CO2 eq. [12] |
| Minimum operation leakage                     | 0.05% [13]                |
| Expected operation leakage                    | 0.1% [31, 13]             |
| Maximum operation leakage                     | 0.5% [13, 1]              |
| Minimum leakage during recovery and recycling | 1% [13]                   |
| Expected leakage recovery and recycling       | 2% [13, 4]                |
| Maximum leakage recovery and recycling        | 5% [13]                   |
| Investment cost per f.u.                      | 1 p.u.                    |

Table 5-6 Parameters for C4FN GIS

| Parameter                                     | Value                    |
|-----------------------------------------------|--------------------------|
| GWP (C4FN)                                    | 2,100 CO2 eq. [57]       |
| GWP (CO2)                                     | 1 CO2 eq.                |
| GWP (O2)                                      | 0 CO2 eq.                |
| Amount of gas per f.u.                        | 30 kg [33]               |
| Volume fraction (C4FN/CO2/O2)                 | 3.5% / 86.5% / 10% [12]  |
| Mass fraction (C4FN/CO2/O2)                   | 0.72% / 98.33% / 0.95%   |
| Manufacturing + transport CO2 footprint       | 28,812 kg of CO2 eq.[12] |
| Minimum operation leakage                     | 0.1%                     |
| Expected operation leakage                    | 0.2% [12]                |
| Maximum operation leakage                     | 1%                       |
| Minimum leakage during recovery and recycling | 1% [13]                  |
| Expected leakage recovery and recycling       | 2% [13]                  |
| Maximum leakage recovery and recycling        | 5% [13]                  |
| Investment cost per f.u.                      | 1 p.u.                   |

Table 5-7 Parameters for Air GIS

| Parameter                               | Value                     |
|-----------------------------------------|---------------------------|
| GWP                                     | 0 CO2 eq.                 |
| Manufacturing + transport CO2 footprint | 37,765 kg of CO2 eq. [12] |
| Air share                               | 95.2%                     |
| Investment cost per f.u.                | 1.2 p.u.                  |

Table 5-8 General parameters

| Parameter           | Value                         |
|---------------------|-------------------------------|
| Device lifetime     | 40 years                      |
| Interest rate       | 4.5% (ECB, data of 2023) [67] |
| HV share            | N(0.5080, 0.1304)             |
| Manufacturing noise | U(0.8, 1.2)                   |

Interest rate is obtained from official sources [67].

The cost comparisons are done in per units with the SF6 functional unit as the base, thus having an investment cost of 1 p.u.

The device's data gives the composition of the gas in volume fractions. However, to calculate CO2 emissions mass fractions are needed. This conversion can be found in Appendix C.

The operation leakage is set to 0.2% in the LCA [12], double the value of the SF6 device, as a conservative answer the lower sensitivity in the monitoring of this technology. Following this reasoning, the minimum and maximum leakages have also been doubled.

Air-base GIS are not available at voltages higher than 145 kV, due to the lower dielectric strength of the gas and technical limits of vacuum breaking. Replacement plans implementing air devices will need to use C4FN devices for voltages higher than this limit. This is represented by the parameter called Air share. Due to lack of data in the Swedish system, it has been calculated based on the German system as analogous [29], as the proportion between SF6 devices installed at EHV and the total number of SF6 devices:

$$Air_{share} = 1 - \frac{FU_{EHV} \cdot FU_{EHV,SF6}}{FU_{EHV} \cdot FU_{EHV,SF6} + FU_{HV} \cdot FU_{HV,SF6}} \quad (5.3)$$

$$Air_{share} = 1 - \frac{3000 \cdot 0.06}{3000 \cdot 0.06 + 25000 \cdot 0.15} = 0.952$$

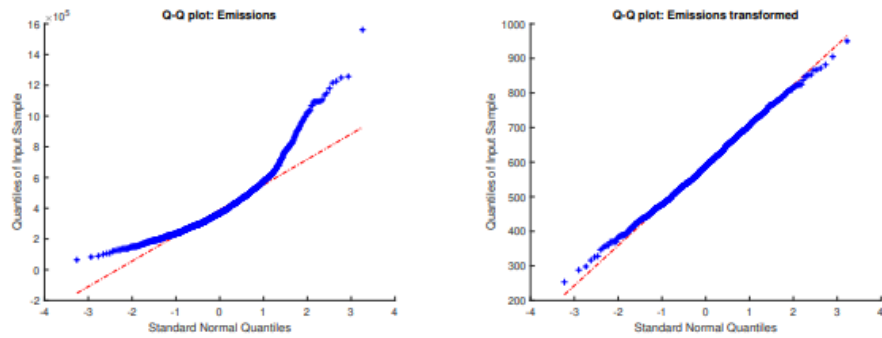
Then, some stochastic elements are introduced to the parameters. Leakage rates are modelled as a PERT PDF. Manufacturing footprint is multiplied by a random number between 0.8 and 1.2 to represent the uncertainty (e.g., a supply crisis of aluminum rises changes the location of the supplier).

### 5.3 TRANSFORMATION OF DATA

In the first simulations of the model it was observed that the data obtained deviated greatly from a normal distribution, as seen in Figure 5-5a. Therefore, the

data (emissions) are transformed using a square root, leading to the results of Figure 5-5b that follow a normal distribution.

$$y = \sqrt{E_{CO2}} \quad (5.4)$$



(a) Q-Q plot of emissions from ANOVA. (b) Q-Q plot of emissions transformed from ANOVA.

Figure 5-5 Q-Q plots. Comparison of normality

## 6 Simulation's definition and characteristics

This Chapter shows the results of the simulations using the model built in the previous section. It is divided in an initial, smaller comparison of the technologies in the standard replacement plan, and a final, larger comparison of all the plans. From the first analysis the better insulating medium is detected, while the second focuses on how to implement it in the system. This simplifies the analysis, as some of the plans might be redundant between each other when focusing on the technology and would only add noise to the first analysis.

This chapter shows figures corresponding to the first scenario for illustrative reasons, as it is more clear and understandable that the huge amount of figures and tables including the four scenarios would have. The other scenarios can be found in Appendix D.

Finally, both the external and internal validity are checked following the indications from the method in Chapter 4, using a sensitivity analysis and checking the hypothesis of the ANOVA.

### 6.1 MAJOR RESULTS

#### 6.1.1 Technology analysis

The ANOVA analysis indicates that at least one technology yields different results across all four scenarios, as the p-value is in the order of  $10^{-60}$ , significantly smaller than the confidence level required,  $\alpha/2 = 0.025$ . The results are shown in Table 6-1. This result reflects the initial expectations, as the GWP of the alternatives considerably lower than that of SF<sub>6</sub>, and it is coherent with previous studies [12] [13].

Table 6-1 ANOVA table. Comparison of technologies. Scenario SF

| Source   | Sum of squares | Degrees of Freedom | Variances  | F        | Prob>F     |
|----------|----------------|--------------------|------------|----------|------------|
| Plans    | 4.1041e+06     | 2                  | 2.0520e+06 | 210.8447 | 5.3439e-70 |
| Residues | 5.8103e+06     | 597                | 9.7324e+03 |          |            |
| Total    | 9.9143e+06     | 599                |            |          |            |

The comparison by pairs using Student's t-distribution (in Table 6-2 and Figure 6-1) shows that the emissions of SF<sub>6</sub> technology are higher than with the alternatives with a great degree of certainty, having P-values of 0. This was the expected result.

More importantly, it also shows that the emissions of C<sub>4</sub>FN are lower than a mixed approach of Air and C<sub>4</sub>FN, and that the difference is statistically significant compared to  $\alpha = 0.05$ .

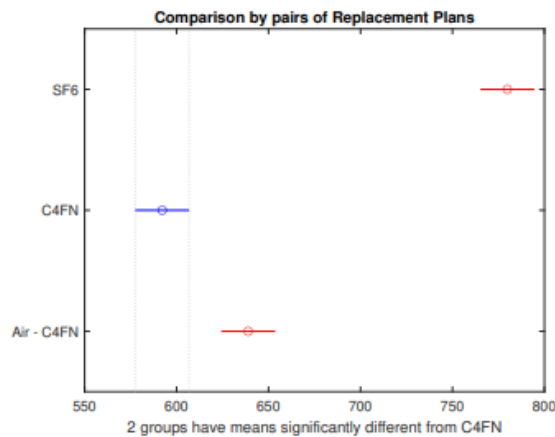


Figure 6-1 Comparison by pairs of mean emissions in Scenario SF. Comparison of technologies

Table 6-2 Comparison by pairs. Comparison of technologies. Scenario SF

| Group | Control Group | Lower Limit | Difference | Upper Limit | P-value    |
|-------|---------------|-------------|------------|-------------|------------|
| SF6   | C4FN          | 170.8526    | 193.974    | 217.0953    | 0          |
| SF6   | Air - C4FN    | 124.4726    | 147.5939   | 170.7152    | 0          |
| C4FN  | Air - C4FN    | -69.5014    | -46.3801   | -23.2587    | 7.7156e-06 |

The histograms and boxplots (Figure 6-2 and Figure 6-3) with the results show a wide range of values, which could indicate that the results are very sensitive to the stochastic nature of the model.

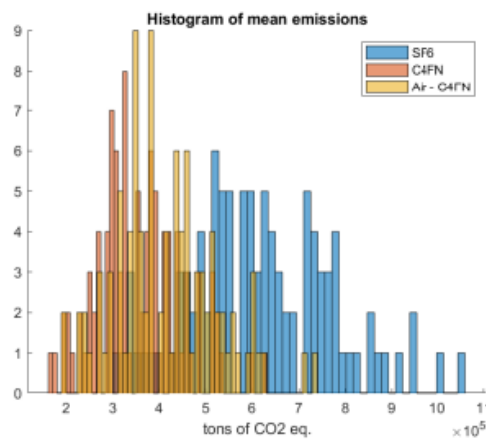


Figure 6-2 Histogram of mean emissions in Scenario SF. Comparison of technologies

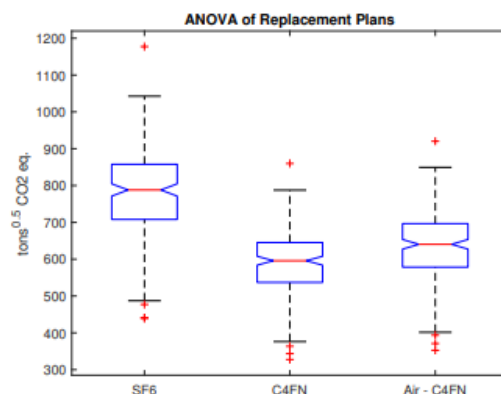
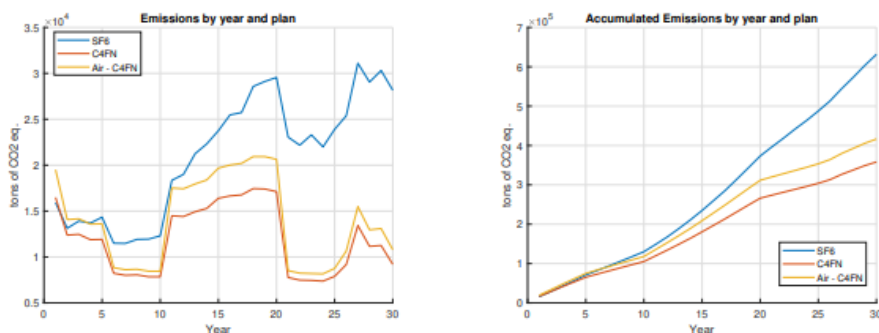


Figure 6-3 Boxplot of mean squared emissions in Scenario SF. Comparison of technologies

The emissions of each type of technology are shown in Figure 6-4 and Table 6-3. The alternative technologies have higher emissions during the first two to three years compared to SF6, especially in the case of Air, which emits 300 to 400 tons more. This shows that the manufacturing phase, in which Air GIS has higher footprint due to being bigger, has more weight than the operation phase.



(a) Mean emissions in Scenario SF. (b) Accumulated mean emissions in Scenario SF. Comparison of technologies

Figure 6-4 Mean emissions. Comparison of technologies in Scenario SF

Table 6-3 Mean emissions. Comparison of technologies

| Technology | Scenario SF<br>Emissions [tons CO2 eq.] | Scenario FM<br>Emissions [tons CO2 eq.] | Scenario EP<br>Emissions [tons CO2 eq.] | Scenario EF<br>Emissions [tons CO2 eq.] |
|------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|
| SF6        | 631,707                                 | 511,680                                 | 625,528                                 | 847,099                                 |
| C4FN       | 358,176                                 | 306,172                                 | 363,741                                 | 479,133                                 |
| Air-C4FN   | 416,464                                 | 352,059                                 | 425,186                                 | 575,131                                 |

Emissions per year show periods of considerably higher values in the shape of a plateau. Comparing the years of these "plateaus" to the evolution of Installed Capacity in Figure 5-3, they have a direct correlation. When the Installed Capacity increases faster (higher slope), like it does in scenario SF in blue between 2030 and 2040, a plateau is seen in the emissions due to the installation of a big quantity of GIS.

The rise of emissions with the rate of IC is expected, as the SF6 stock is derived from the projection of this variable in the future. However, the shape of the plateau indicates, again, that the manufacturing phase has more weight in the emissions: the manufacturing footprint is related to the rate of installation, and thus drops

when the slope is lower. Leakage during operation is related to the absolute IC, so it keeps growing as long as the rate of installation is positive but is independent of its specific value; if the latter was dominant, we would not see a drop from the plateau.

The case with the continuation of SF6 shows a growing tendency: every year has, on average, higher emissions than the previous year. This is because the impact of operation leakage is more significant there than in the alternative technologies, which have, instead, more constant values across the years.

From the analysis of technologies, it is concluded that the use of C4FN exclusively gives the best results, with a reduction of emissions, on average, of 42.19% compared to continuing SF6. The use of Air devices supported by C4FN only reduces emissions by 32.35%.

### 6.1.2 Phase out plan analysis

The ANOVA analysis indicates that at least one replacement plan yields different results across all four scenarios, as the p-value is in the order of 10<sup>-150</sup> and beyond, significantly smaller than the confidence level required,  $\alpha/2 = 0.025$ . The results are shown in Table 6-4. However, this was already expected, as from the technology analysis done previously it is known that the Standard plan with C4FN and the same plan with Air - C4FN have differences statistically significant.

Table 6-4 ANOVA table. Comparison of phase-out plans, Scenario SF

| Source   | Sum of squares | Degrees of Freedom | Variances  | F        | Prob>F      |
|----------|----------------|--------------------|------------|----------|-------------|
| Plans    | 9.7951e+06     | 7                  | 1.3993e+06 | 185.0759 | 1.0765e-200 |
| Residues | 1.2037e+07     | 1592               | 7.5607e+03 |          |             |
| Total    | 2.1832e+07     | 1599               |            |          |             |

Table 6-5 shows the comparison of pairs of replacement plans. This time some overlap is seen between plans. For example, in scenario SF, the Standard plan with C4FN and the Half Life plan with a mix of Air and C4FN has a p-value of 0.99, higher than the confidence level required. The more drastic measures of the Half life plan, substituting a big portion of SF6 GIS, thus reducing considerably future operational leakage of the gas, makes Air devices competitive against a slower implementation of C4FN GIS. This shows that, even though Air GIS has a higher impact as a standalone technology, the way of its implementation can make it competitive against C4FN solutions.

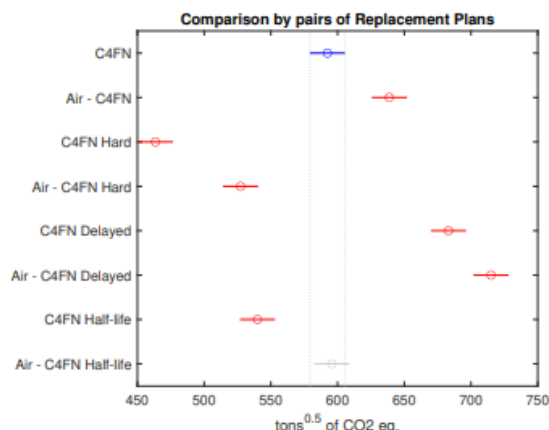


Figure 6-5 Comparison by pairs of mean emissions in Scenario SF. Comparison of phase-out plans

Table 6-5 Comparison by pairs. Comparison of phase-out plans, Scenario SF

| Group              | Control Group        | Lower Limit | Difference | Upper Limit | P-value    |
|--------------------|----------------------|-------------|------------|-------------|------------|
| C4FN               | Air - C4FN           | -72.7342    | -46.3801   | -20.026     | 2.6497e-06 |
| C4FN               | C4FN Hard            | 102.526     | 128.8802   | 155.2343    | 0          |
| C4FN               | Air - C4FN Hard      | 38.7164     | 65.0705    | 91.4247     | 1.3025e-12 |
| C4FN               | C4FN Delayed         | -117.0741   | -90.7199   | -64.3658    | 0          |
| C4FN               | Air - C4FN Delayed   | -148.9527   | -122.5986  | -96.2444    | 0          |
| C4FN               | C4FN Half-life       | 26.0226     | 52.3767    | 78.7308     | 4.5914e-08 |
| C4FN               | Air - C4FN Half-life | -29.6621    | -3.308     | 23.0461     | 0.99995    |
| Air - C4FN         | C4FN Hard            | 148.9061    | 175.2602   | 201.6144    | 0          |
| Air - C4FN         | Air - C4FN Hard      | 85.0965     | 111.4506   | 137.8047    | 0          |
| Air - C4FN         | C4FN Delayed         | -70.694     | -44.3399   | -17.9857    | 9.3848e-06 |
| Air - C4FN         | Air - C4FN Delayed   | -102.5726   | -76.2185   | -49.8644    | 9.5307e-18 |
| Air - C4FN         | C4FN Half-life       | 72.4027     | 98.7568    | 125.1109    | 0          |
| Air - C4FN         | Air - C4FN Half-life | 16.718      | 43.0721    | 69.4262     | 2.0007e-05 |
| C4FN Hard          | Air - C4FN Hard      | -90.1637    | -63.8096   | -37.4555    | 4.1999e-12 |
| C4FN Hard          | C4FN Delayed         | -245.9542   | -219.6001  | -193.246    | 0          |
| C4FN Hard          | Air - C4FN Delayed   | -277.8328   | -251.4787  | -225.1246   | 0          |
| C4FN Hard          | C4FN Half-life       | -102.8576   | -76.5034   | -50.1493    | 6.7884e-18 |
| C4FN Hard          | Air - C4FN Half-life | -158.5423   | -132.1882  | -105.834    | 0          |
| Air - C4FN Hard    | C4FN Delayed         | -182.1446   | -155.7905  | -129.4364   | 0          |
| Air - C4FN Hard    | Air - C4FN Delayed   | -214.0232   | -187.6691  | -161.315    | 0          |
| Air - C4FN Hard    | C4FN Half-life       | -39.048     | -12.6938   | 13.6603     | 0.82877    |
| Air - C4FN Hard    | Air - C4FN Half-life | -94.7327    | -68.3785   | -42.0244    | 5.1754e-14 |
| C4FN Delayed       | Air - C4FN Delayed   | -58.2327    | -31.8786   | -5.5245     | 0.0060148  |
| C4FN Delayed       | C4FN Half-life       | 116.7425    | 143.0967   | 169.4508    | 0          |
| C4FN Delayed       | Air - C4FN Half-life | 61.0578     | 87.4119    | 113.7661    | 0          |
| Air - C4FN Delayed | C4FN Half-life       | 148.6212    | 174.9753   | 201.3294    | 0          |
| Air - C4FN Delayed | Air - C4FN Half-life | 92.9364     | 119.2906   | 145.6447    | 0          |
| C4FN Half-life     | Air - C4FN Half-life | -82.0388    | -55.6847   | -29.3306    | 3.9038e-09 |

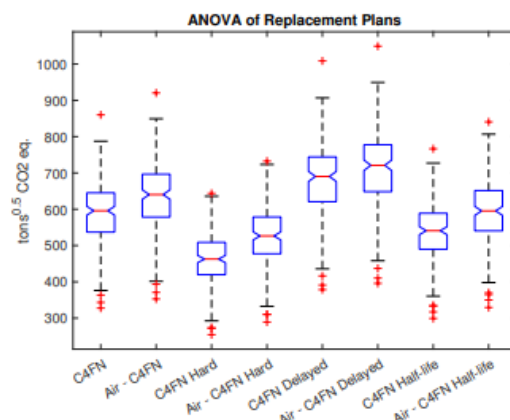
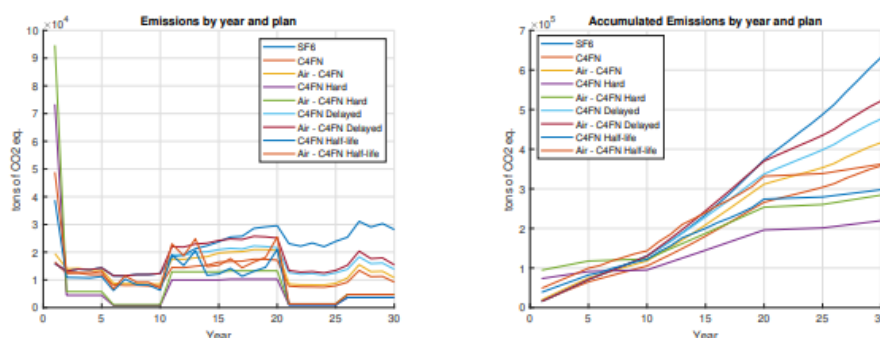


Figure 6-6 Boxplot of mean squared emissions in Scenario SF. Comparison of phase-out plans



(a) Mean emissions in Scenario SF. (b) Accumulated mean emissions in Scenario SF. Comparison of phase-out plans.

Figure 6-7 Mean emissions. Comparison of phase-out plans in Scenario SF

Table 6-6 Mean emissions. Comparison of phase-out plans. Scenario SF

| Technology<br>Technology | Mean<br>[tons CO2 eq.] | Minimum<br>[tons CO2 eq.] | Maximum<br>[tons CO2 eq.] | Standard deviation<br>[tons CO2 eq.] |
|--------------------------|------------------------|---------------------------|---------------------------|--------------------------------------|
| SF6                      | 631,707                | 192,997                   | 1,386,008                 | 181,203                              |
| C4FN                     | 358,176                | 107,269                   | 739,441                   | 100,313                              |
| Air-C4FN                 | 416,464                | 124,384                   | 846,877                   | 116,673                              |
| C4FN Hard                | 219,458                | 64,716                    | 414,297                   | 62,869                               |
| Air-C4FN Hard            | 284,045                | 83,708                    | 536,375                   | 81,390                               |
| C4FN Delayed             | 476,403                | 143,331                   | 1,017,136                 | 134,281                              |
| Air-C4FN Delayed         | 521,864                | 156,679                   | 1,100,943                 | 146,760                              |
| C4FN Half-life           | 297,651                | 89,480                    | 587,625                   | 83,597                               |
| Air-C4FN Half-life       | 362,239                | 108,450                   | 706,686                   | 101,986                              |

Hard replacement using C4FN devices shows the least emissions across all four scenarios, and the difference is statistically significant with all other plans. On average, it reduces emissions by 63.27%.

Hard replacement using Air and C4FN devices follows closely with an average reduction of 52.45%. However, it is less consistent. The difference is not statistically significant against the Half life plan using C4FN across all scenarios, with an average reduction of 51.33%, and even beats it in Scenario EF (see Appendix D). In this last scenario, which has the highest increase in IC, and therefore the manufacturing footprint is even more predominant, hard replacement with air

technologies is also not significantly different than the Standard plan with C4FN, with a P-value of 0.42.

The Standard plan has an average reduction of 42.19% with C4FN, and 32.35% with Air and C4FN GIS, as seen in the previous section. The impact of delaying the plan 10 years, by 2030, is an increase of 38.17% (even surpassing 40% in Scenario EP) and 28.61% respectively compared to the emissions of the Standard plans.

The Standard plans do not substitute all of the SF6 stock by the end of 2050, as seen in Table 6-7, and it will not do so until the end of the lifetime of the devices installed in 2020, in 2060.

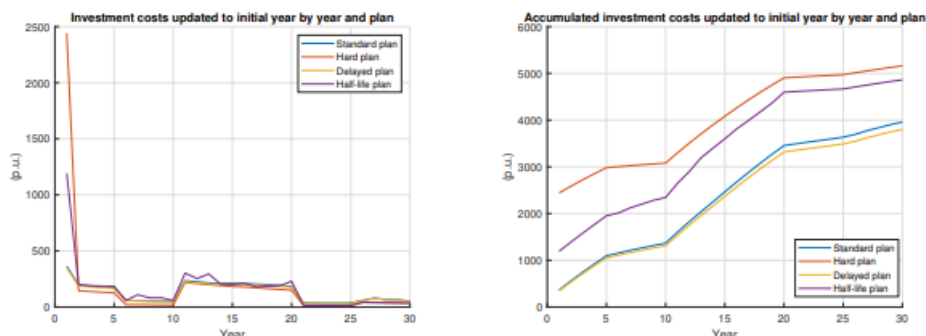
Final stock of C4FN, the gas with the highest GWP in the alternative technologies, is small, with at most 3.6681 tons, compared to the 153 tons of SF6 that are currently installed as reported by Swedenergi [3]. The size of the stock, along with it having a much smaller GWP (2,100 vs 23,500), explains why the operational leakage of the gas has less weight on total emissions than the manufacturing footprint of the device.

**Table 6-7 Gas stock for one random simulation, in tons, in 2050. Scenario SF**

| Plan               | SF6      | C4FN   | CO2      | Air      |
|--------------------|----------|--------|----------|----------|
| SF6                | 714.9730 | 0      | 0        | 0        |
| C4FN               | 58.5446  | 3.4674 | 475.9510 | 0        |
| Air-C4FN           | 58.5446  | 0.1588 | 21.7993  | 516.8777 |
| C4FN Hard          | 0        | 3.6681 | 503.5032 | 0        |
| Air-C4FN Hard      | 0        | 0.1680 | 23.0612  | 572.7409 |
| C4FN Delayed       | 212.7098 | 2.7407 | 376.2001 | 0        |
| Air-C4FN Delayed   | 212.7098 | 0.1255 | 17.2305  | 403.1078 |
| C4FN Half-life     | 0        | 3.6681 | 503.5032 | 0        |
| Air-C4FN Half-life | 0        | 0.1680 | 23.0612  | 572.7409 |

It shows a wide range of values, as observed in the histograms of the previous section. The results from the simulation have a standard deviation of around 28% of the mean value. This seems to indicate that some of the stochastic parameters can influence the emissions significantly. This is studied in detail in the Sensitivity Analysis.

The cost analysis is less precise for lack of information, but some conclusions can be made from the graphs in Figure 6-8 Mean costs. Comparison of phase-out plans in Scenario SF. The investment cost is tied to the manufacturing and installation of new GIS, and therefore behave the same as the emissions (in which manufacturing had more weight).



(a) Mean costs in Scenario SF. Comparison of phase-out plans. (b) Accumulated mean costs in Scenario SF. Comparison of phase-out plans.

Figure 6-8 Mean costs. Comparison of phase-out plans in Scenario SF

As discussed in the introduction, the Hard replacement plan has the highest costs. It requires a very high investment at front, being around 7 times higher than the more moderate plans. The latter plans have higher costs in the following years, as they have to replace more devices, but even then the Hard replacement plans have more accumulated costs. At year 30, the difference has gone down to 1.5 times in the worst case, considerably less than the difference in the first year.

The need for SF<sub>6</sub> is an important factor. As it should be obvious, more aggressive scenarios will require a higher budget. However, as more units are installed the difference between plans is reduced. In scenario EF, the Hard Plan is only 1.25 times higher than the Standard, compared to the 1.5 seen in scenario FM (see Appendix D).

This difference is, however, not statistically significant in the ANOVA.

## 6.2 SENSITIVITY ANALYSIS

The sensitivity analysis covers four groups of parameters: the power system model (relation between IC and SF<sub>6</sub> stock, and share of stock in HV), and the three technologies.

The results are more sensitive to the power system model parameters, where variations higher than 5% and even 15% are observed, as shown in Table 6-8 and Table 6-9. These directly affect the value given to the stock of the gases, which is the main contributor of the emissions. Their underestimation leads to overly optimistic results, which could wrongly indicate more relaxed plans as viable. The overestimation poses the same problem, leading to make a bigger investment than necessary.

Emissions are linear in the range  $\pm 10\%$  and no direction is significantly more impactful.

Table 6-8 Change of mean emissions due to input conditions 1. Linear regression parameters

| Technology         | Original emissions<br>[tons CO2 eq. ] | Linear Regression<br>Intercept -10% | Linear Regression<br>Intercept +10% | Linear Regression<br>Slope +10% | Linear Regression<br>Slope -10% |
|--------------------|---------------------------------------|-------------------------------------|-------------------------------------|---------------------------------|---------------------------------|
| SF6                | 614,252                               | -6.27%                              | +6.27%                              | +15.03%                         | -15.03%                         |
| C4FN               | 350,162                               | -3.32%                              | +3.32%                              | +9.44%                          | -9.44%                          |
| Air-C4FN           | 407,473                               | -3.69%                              | +3.70%                              | +10.10%                         | -10.10%                         |
| C4FN Hard          | 215,777                               | -5.39%                              | +5.39%                              | +15.32%                         | -15.32%                         |
| Air-C4FN Hard      | 279,276                               | -5.39%                              | +5.40%                              | +15.34%                         | -15.33%                         |
| C4FN Delayed       | 464,468                               | -8.29%                              | +8.29%                              | +17.36%                         | -17.37%                         |
| Air-C4FN Delayed   | 509,166                               | -7.57%                              | +7.57%                              | +16.87%                         | -16.88%                         |
| C4FN Half-life     | 291,700                               | -3.99%                              | +3.99%                              | +11.33%                         | -11.33%                         |
| Air-C4FN Half-life | 355,198                               | -4.24%                              | +4.24%                              | +11.78%                         | -11.78%                         |

Table 6-9 Change of mean emissions due to input conditions 2. HV share

| Technology         | Original emissions<br>[tons CO2 eq. ] | Mean of Normal<br>Distribution -10% | Mean of Normal<br>Distribution +10% | Standard<br>Deviation +10% | Standard<br>Deviation -10% |
|--------------------|---------------------------------------|-------------------------------------|-------------------------------------|----------------------------|----------------------------|
| SF6                | 614,252                               | -10.07%                             | +10.06%                             | -0.065%                    | +0.062%                    |
| C4FN               | 350,162                               | -10.07%                             | +10.06%                             | -0.069%                    | +0.061%                    |
| Air-C4FN           | 407,473                               | -10.07%                             | +10.07%                             | -0.070%                    | +0.062%                    |
| C4FN Hard          | 215,777                               | -10.08%                             | +10.08%                             | -0.081%                    | +0.078%                    |
| Air-C4FN Hard      | 279,276                               | -10.08%                             | +10.08%                             | -0.081%                    | +0.078%                    |
| C4FN Delayed       | 464,468                               | -10.07%                             | +10.06%                             | -0.065%                    | +0.061%                    |
| Air-C4FN Delayed   | 509,166                               | -10.07%                             | +10.06%                             | -0.066%                    | +0.061%                    |
| C4FN Half-life     | 291,700                               | -10.06%                             | +10.07%                             | -0.064%                    | +0.073%                    |
| Air-C4FN Half-life | 355,198                               | -10.07%                             | +10.08%                             | -0.064%                    | +0.075%                    |

Of the three technologies, the emissions are more sensitive to the current SF6 GIS, as it is the main contributor.

Results are very sensitive to the GWP. However, given that it is obtained directly from the IPCC [2], it is a trusted value. The amount of gas per functional unit also has high impact: overestimating it reduces the emissions considerably. This might seem counter-intuitive if we look at the emissions of one unit, as more gas leads to more leakage. However, since the total amount on the system is fixed as an input, a higher amount per unit means less units in total, and, as discussed in the previous sections, the manufacturing phase (and, therefore, the number of units) has more weight on the results.

In the plans with longer presence of this technology, the leakage ratio during operation is also significant. This is important because, even though the leakage is limited to 0.1% on paper, it usually increases with use or, more drastically, with faults or damage. On contrast, the leakage at the end of its lifetime, in the recovery and recycling of the gas after it is decommissioned, has very little impact due to its rarer occurrence.

Table 6-10 Change of mean emissions due to input conditions 3. SF6 parameters

| Technology             | Original emissions<br>[tons CO2 eq. ] | GWP +10% | amount per<br>f.u. +10% | Manufacturing<br>footprint +10% |
|------------------------|---------------------------------------|----------|-------------------------|---------------------------------|
| SF6                    | 614,252                               | +7.29%   | -2.46%                  | +2.70%                          |
| C4FN                   | 350,162                               | +4.48%   | -5.02%                  | 0%                              |
| Air-C4FN               | 407,473                               | +3.85%   | -5.59%                  | 0%                              |
| C4FN Hard              | 215,777                               | +0.07%   | -9.03%                  | 0%                              |
| Air-C4FN Hard          | 279,276                               | +0.05%   | -9.04%                  | 0%                              |
| C4FN Delayed           | 464,468                               | +5.96%   | -3.67%                  | +0.79%                          |
| Air-C4FN Delayed       | 509,166                               | +5.44%   | -4.14%                  | +0.72%                          |
| C4FN Half-life CO2 eq. | 291,700                               | +2.66%   | -6.67%                  | 0%                              |
| Air-C4FN Half-life     | 355,198                               | +2.18%   | -7.10%                  | 0%                              |

Table 6-11 Change of mean emissions due to input conditions 4. SF6 parameters

| Technology         | Original emissions<br>[tons CO2 eq. ] | Minimum leakage<br>in operation +10% | Normal leakage<br>in operation +10% | Maximum leakage<br>in operation +10% |
|--------------------|---------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|
| SF6                | 614,252                               | +0.34%                               | +2.71%                              | +3.42%                               |
| C4FN               | 350,162                               | +0.16%                               | +1.29%                              | +1.61%                               |
| Air-C4FN           | 407,473                               | +0.14%                               | +1.10%                              | +1.38%                               |
| C4FN Hard          | 215,777                               | 0%                                   | 0%                                  | 0%                                   |
| Air-C4FN Hard      | 279,276                               | 0%                                   | 0%                                  | 0%                                   |
| C4FN Delayed       | 464,468                               | +0.26%                               | +2.05%                              | +2.58%                               |
| Air-C4FN Delayed   | 509,166                               | +0.24%                               | +1.87%                              | +2.36%                               |
| C4FN Half-life     | 291,700                               | +0.06%                               | +0.44%                              | +0.55%                               |
| Air-C4FN Half-life | 355,198                               | +0.05%                               | +0.36%                              | +0.45%                               |

Table 6-12 Change of emissions due to input conditions 5. SF6 parameters

| Technology         | Original emissions<br>[tons CO2 eq. ] | Minimum leakage<br>in decommission +10% | Normal leakage<br>in decommission +10% | Maximum leakage<br>in decommission +10% |
|--------------------|---------------------------------------|-----------------------------------------|----------------------------------------|-----------------------------------------|
| SF6                | 614,252                               | +0.06%                                  | +0.46%                                 | +0.29%                                  |
| C4FN               | 350,162                               | +0.10%                                  | +0.80%                                 | +0.51%                                  |
| Air-C4FN           | 407,473                               | +0.09%                                  | +0.69%                                 | 0.44%                                   |
| C4FN Hard          | 215,777                               | +0.005%                                 | +0.04%                                 | +0.03%                                  |
| Air-C4FN Hard      | 279,276                               | +0.003%                                 | +0.03%                                 | +0.02%                                  |
| C4FN Delayed       | 464,468                               | +0.08%                                  | +0.61%                                 | +0.39%                                  |
| Air-C4FN Delayed   | 509,166                               | +0.07%                                  | +0.55%                                 | +0.35%                                  |
| C4FN Half-life     | 291,700                               | +0.11%                                  | +0.91%                                 | +0.58%                                  |
| Air-C4FN Half-life | 355,198                               | +0.09%                                  | +0.75%                                 | +0.48%                                  |

The results are not sensitive to the parameters of new C4FN GIS, except in the manufacturing phase. This is probably due to the small amount of the gas involved in each unit. The manufacturing footprint, however, has great influence, especially in the more drastic plans (Hard and Half-life).

Table 6-13 Change of mean emissions due to input conditions 6. C4FN parameters

| Technology         | Original emissions<br>[tons CO2 eq. ] | GWP +10% | amount per<br>f.u. +10% | Mass fraction of C4FN<br>in mixture +10% | Manufacturing<br>footprint +10% |
|--------------------|---------------------------------------|----------|-------------------------|------------------------------------------|---------------------------------|
| C4FN               | 350,162                               | 0%       | 0%                      | 0%                                       | +5.52%                          |
| Air-C4FN           | 407,473                               | 0%       | 0%                      | 0%                                       | +0.22%                          |
| C4FN Hard          | 215,777                               | 0%       | 0%                      | 0%                                       | +9.93%                          |
| Air-C4FN Hard      | 279,276                               | 0%       | 0%                      | 0%                                       | +0.35%                          |
| C4FN Delayed       | 464,468                               | 0%       | 0%                      | 0%                                       | 3.25%                           |
| Air-C4FN Delayed   | 509,166                               | 0%       | 0%                      | 0%                                       | 0.14%                           |
| C4FN Half-life     | 291,700                               | 0%       | 0%                      | 0%                                       | 7.34%                           |
| Air-C4FN Half-life | 355,198                               | 0%       | 0%                      | 0%                                       | 0.28%                           |

Table 6-14 Change of mean emissions due to input parameters 7. C4FN parameters

| Technology         | Original emissions<br>[tons CO2 eq.] | Minimum leakage<br>in operation +10% | Normal leakage<br>in operation +10% | Maximum leakage<br>in operation +10% |
|--------------------|--------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|
| C4FN               | 350,162                              | 0%                                   | 0%                                  | 0%                                   |
| Air-C4FN           | 407,473                              | 0%                                   | 0%                                  | 0%                                   |
| C4FN Hard          | 215,777                              | 0%                                   | 0%                                  | 0%                                   |
| Air-C4FN Hard      | 279,276                              | 0%                                   | 0%                                  | 0%                                   |
| C4FN Delayed       | 464,468                              | 0%                                   | 0%                                  | 0%                                   |
| Air-C4FN Delayed   | 509,166                              | 0%                                   | 0%                                  | 0%                                   |
| C4FN Half-life     | 291,700                              | 0%                                   | 0%                                  | 0%                                   |
| Air-C4FN Half-life | 355,198                              | 0%                                   | 0%                                  | 0%                                   |

The manufacturing footprint of Air GIS has a similar sensitivity. However, it can be more relevant, as if the real value is smaller than the one reported, it could make it more competitive.

Table 6-15 Change of mean emissions due to input conditions 8. Air parameters

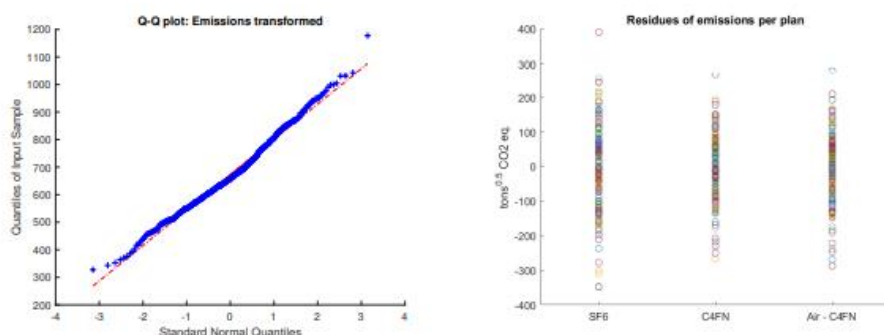
| Technology         | Original emissions<br>[tons CO2 eq.] | Air share +10% | Air share -10% | Manufacturing<br>footprint +10% | Manufacturing<br>footprint -10% |
|--------------------|--------------------------------------|----------------|----------------|---------------------------------|---------------------------------|
| Air-C4FN           | 407,473                              | +1.41%         | -1.41%         | +5.93%                          | -5.93%                          |
| Air-C4FN Hard      | 279,276                              | +2.27%         | -2.27%         | +9.59%                          | -9.59%                          |
| Air-C4FN Delayed   | 509,166                              | +0.88%         | -0.88%         | +3.70%                          | -3.70%                          |
| Air-C4FN Half-life | 355,198                              | +1.79%         | -1.79%         | +7.54%                          | -7.54%                          |

### 6.3 VALIDITY ANALYSIS

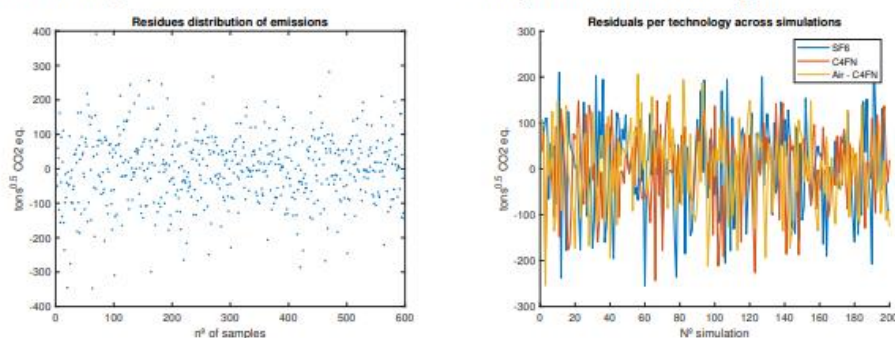
The ANOVA can be used under three assumptions: that the responses follow a normal distribution, that the distributions of the different plans have the same variance (homodestacity), and that the observations are independent of each other.

The normal distribution is checked with the Q-Q plots, as discussed in Chapter 4. They can be seen in Figure 6-9a and Figure 6-10a. In both cases the residuals are distributed along the red line, so it can be concluded that it follows smaller than the threshold (3). From both series of figures it can be affirmed that the model is homodestacitic.

Finally, no obvious pattern is discerned from the residuals across observations in Figure 6-9d and Figure 6-10d. Dependence between observations is not seen directly in these.

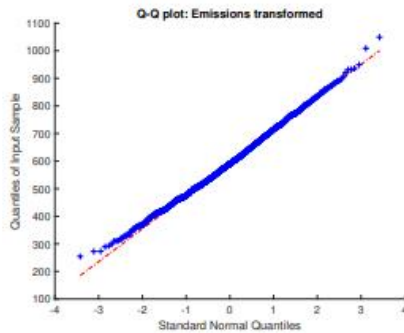


(a) Q-Q plot in Scenario SF. Comparison of technologies (b) Residuals per plan in Scenario SF. Comparison of technologies

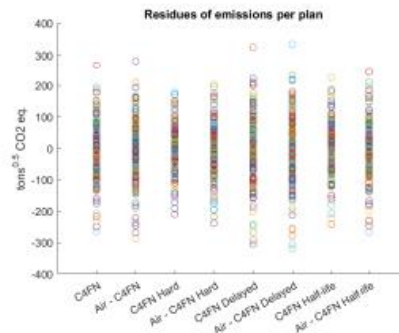


(c) Residuals in Scenario SF. Comparison of technologies (d) Residuals in Scenario SF. Comparison of technologies

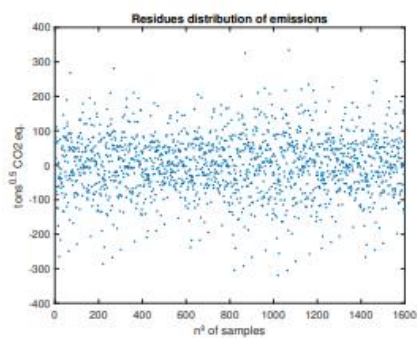
Figure 6-9 Graphs for validity check. Comparison of technologies



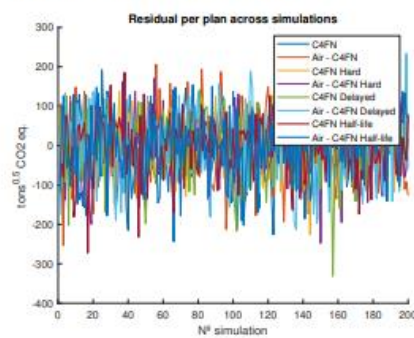
(a) Q-Q plot in Scenario SF. Comparison of phase-out plans.



(b) Residuals per plan in Scenario SF. Comparison of phase-out plans.



(c) Residuals in Scenario SF. Comparison of phase-out plans.



(d) Residuals in Scenario SF. Comparison of phase-out plans.

Figure 6-10 Graphs for validity check. Comparison of phase-out plans

## 7 Conclusions and future work

### 7.1 CONCLUSIONS ON RESULTS

For every type of replacement plan (standard, hard replacement, etc.) the simulations have shown a statically significant advantage towards C4FN technologies. These simulations agree with the studies from others researchers covered in the background, specially the assessments by Kieffel et al., (2016) [18] and Hitachi Energy [12].

Its impact is significant enough to show the need for action in the replacement of SF6, as its implementation with the standard plan can save between 200 and 370 ktons of CO2eq., 42.19% on average. Meanwhile, a delay of the replacement by 10 years would increase the emissions approximately 40% compared to acting now.

These results show the same percentile reduction as previous studies; Billen et al., (2020) [13], evaluating all of Europe, simulated saving from 20 to 10 Mtons of CO2 eq. in 2050 changing from SF6 to C4FN, around 50% reduction.

Surprisingly, technologies using air as its insulator have higher emissions during their lifetime in spite of using an alternative with GWP 0. Its implementation in a standard plan would only reduce emissions by 32.35% on average.

Both the simulations and the sensitivity analysis show that the most important factor in the alternatives is the manufacturing footprint. This penalizes the latter technologies because, with lower insulation capabilities, they need higher volume or mechanical specifications and increases the impact of construction.

Direct leakage during operation is relevant when discussing SF6 due to the extremely high GWP values. For C4FN, due to the small fraction of the gas in the mixture, its impact is small, as seen in the simulations and the sensitivity analysis.

#### **Impact of the replacement plan.**

The Hard replacement plan is the one that reduces emissions the most, 63.27%, approximately 20% more than the Standard plan, or 120 ktons of CO2 eq. However, its economical and logistical impact is considerably larger. Its initial investment is seven times higher and, although the difference decreases over time, the accumulated costs are higher during the whole period. The efficiency of resources is low, as it reduces emissions by less than 3% per 100% increase on the initial budget.

Considering that the system has 153 tons of SF6, and one functional unit uses 63 kg, there are 2,429 units. If each unit costs \$500,000 [34], the total investment rises to 13 billion SEK (an underestimation of the value discussed in the introduction). It also results in a loss of assets of M\$594 if we consider linear amortization.

Furthermore, the hard replacement plan would mean that those 2,429 units need to be paralyzed. Coordinating all of these operations would be very complex, energy supply would be very delicate, and other expansions of the grid would have less resources.

It would also be a complicated endeavor for the manufacturers that need to supply the devices. Since the introduction of the technology in 2016, GE has done installations in 40+ sites under 145 kV, and 2 sites under 420 kV. The Hard Replacement plan would require intervention on 175 sites [9]. This level of supply might not be possible.

Increasing the cut-off line to devices with over 20 years of operation (Half life replacement plan) does not improve the shortcomings. It still has a higher impact on emissions than the Standard plan, with a reduction of 51.33%. But this cut-off still impacts over 60% of the devices installed, and a loss of assets of M\$71 on the first year, increasing every year until all devices are finally replaced twenty years later.

### **Choice of technologies.**

The most viable alternatives are mixture gases based on the fluoronitrile NOVEC™ 4710, and air. The former can have similar performance to SF6 even at EHV, and its GWP is considerably lower at around 300. Air, even though it has GWP 0, faces several challenges. Its lower insulation properties and null breaking capabilities make necessary devices of bigger volume with higher environmental impact on manufacturing and less viability in the highest voltage levels.

C4FN technology is already in use on some substations, promoted mainly by General Electric and Hitachi Energy. It can give similar performance to SF6 even at EHV levels, which allows for minimal modifications compared to the current system. Thus, it can maintain a similar CO2 footprint from manufacturing, and its installation is flexible, not needing big modifications of the site.

Its mixture with a buffer gas, called g3, has a GWP in the order of 300. This is higher than the objectives of the future European regulation [50], which wants to limit applications with GWP higher than 1. However, it is included in the derogations, which will allow applications with GWP up to 1,000 if no other alternatives exist. In the higher voltage levels there are no other mature alternatives, as it has been agreed by experts (ENTSO-e [8]) and shown in this project, so it is expected that this technology will be allowed.

Air-based devices would comply with the stricter requirements of the latter regulation. However, they have many challenges to be implemented adequately. On the simulations they have worse results due to the high manufacturing footprint. However, on the sensitivity analysis is seen that any reduction over the estimated footprint would have a big impact on this technology's viability. A higher scrutiny on the process is recommended in case of using this option.

More strict plans might be better in this case, as the higher saving of eliminating SF6 early can compensate the higher cost of manufacturing. But this is still difficult considering the economical and logistic factors. They are also bigger devices, which would add to the problem with the necessity of further construction work to adapt the site.

Additionally, air-based devices are more limited for two reasons. First, the size might limit them in closed or smaller sites. Although it is less of an issue in HV

than in MV, some sites might have size restrictions that do not allow to replace their current switchgear with a bigger one. This eliminates air-devices as an option or increases their installation cost adding construction modifications to the site. Second, the technology is only developed up to 145 kV, and other alternatives such as C4FN would still be needed for higher levels.

### **Considerations of the model.**

This project has focused on the whole system using publicly available data. The sensitivity analysis shows that the model of the system is very relevant on the results, both to the linear regression between capacity and SF6 stock, and to the HV distribution.

The monitoring of SF6 has been historically very poor, even with the introduction of the inventories by the UNFCCC. This has been noted by many people, like Billen et al., (2020) [13] and Burges et al., (2018) [29], due to the underestimation of emissions from the reports compared to other methods or the lack of data from some countries. In this report it also has been noted in the lack of information of in which devices is the gas used, which has made some extra assumptions be necessary.

The simulations in this project do a good job of identifying main factors to consider and showing the tendencies of different policies, contrasted to the results of other studies. However, the specific results on emissions quantity are based on the model, which might suffer from poor information.

In the future, this project should be expanded with more data and scrutiny. Companies could use the principles of the project, and the main factors identified to do more exhaustive simulations with, hopefully, more detailed inventories on devices, SF6 stocks, date of installations, costs, etc.

## **7.2 EVALUATION OF THE SUCCESS OF THE PROJECT**

This project had three goals: investigate SF6-free alternatives, how they should be implemented in the system maintaining Eco-Eco sustainability, and what role could monitoring and machine learning have in the replacement.

There are many interesting alternatives currently being studied by researchers, and some of them are even being applied to actual devices already. This project has been successful in reviewing the information from multiple studies and identifying the strengths and weaknesses of each.

The second goal has been investigated in the project with the statistical analysis of simulations projecting future emissions and costs. The resources were limited for this step, as had been discussed, which required the use of assumptions and to reduce the scope.

Assessing all devices (switchgear at both MV and HV, instrument transformers, gas insulated lines) at the same time is a very complex endeavor; each has different characteristics, lifetimes, monitoring protocols, etc. Adding to this the fact that the NIR only includes total amount, the scope needed to be reduced. The simulation

focused just on HV switchgears. This, however, can also be seen as an advantage, as it allowed the project to be more focused on the highest impact area.

The model and simulations have been successful in showing the impact of the different alternatives. It has passed the internal validity checks, and the results are in line with other studies. For example, Billen et al., (2020) [13] estimate an impact of SF6 in 2050 of 20 Mtons of CO<sub>2</sub>eq., and a reduction to 10 MTons with C4FN, approximately a 50% reduction. This project shows results in the same direction, with an average reduction of 42%.

It was also successful in identifying important factors in the analysis. The biggest factor on emissions found was the manufacturing phase, which explained the results seen for air devices.

The third goal is the weaker part of this project. The scope would have been excessively big if it was included in a more practical manner, as it was initially the intention, and it also would have needed many resources. As it is, the discussion from the literature review shows some interesting directions and ideas, but it is supported on subjective evaluations and not on objective results.

### 7.3 EVALUATION OF THE SUCCESS OF THE PROJECT

This area of study is very important for its economical and environmental impact on the future of the power system, and it should be continued on following projects. The next step should be for the companies responsible to take the main ideas of the assessment model and apply them to smaller parts of the system, going from a large-scale model but less detail to a more detailed smaller model.

As it stands, the results from this project give general trends and factors, but the individual companies that have to make the decisions have more information than what has been considered. Whether their site allows for a bigger device or not, what budget they can manage, scheduling goals. The proposed follow-up projects studying smaller parts of the system would help consider these more unique factors.

Future work should also be focused on other devices. MV switchgears, although they have less environmental impact, are the majority of the system and could have more economical needs. Other types of devices suffer from poor inventorying, making their study difficult, but they have high emissions, and their investigation is also important. The framework of the model and simulations used in this project should be useful to build the future work.

### 7.4 CLOSING REMARKS

In conclusion, the project has been successful. The three research questions have been answered. It constitutes an exhaustive literature review that can be very useful for further research on the area. And the simulations identify the main factors that companies need to consider in the replacement, shows general future trends, and serves as a solid tested framework for future work.

The project has a positive impact on the 2030 Agenda showing the progress of the energy system under different circumstances. There have been, however, some limitations due to lack of data, that should be addressed in future projects.

## 8 Appendix A Matlab Code

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# REPLACEMENT OF SULFUR HEXAFLUORIDE (SF<sub>6</sub>) EQUIPMENT IN THE POWER SYSTEM

Sulphur hexafluoride (SF<sub>6</sub>) is a gas used as the insulator medium of high voltage equipment in substations due to its very high dielectric strength and recovery properties after an arcing fault. However, it has an extremely high Global Warming Potential, 23,500, that makes leakage from the equipment a serious environmental problem. As the current equipment reaches the end of its lifetime and more strict regulations are introduced in the EU, companies are looking into more sustainable alternatives to replace them. This project studied the challenges of the transition for High Voltage Gas Insulated Substations.

## A new step in energy research

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