Concept for SF_6-free transmission and distribution of electrical energy

Final report

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

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1 Executive summary

In electrical energy technologies, the gas sulphur hexafluoride (SF_6) currently plays a key role as an insulating and arc-quenching medium, particularly in switchgear. In addition to its many advantages in terms of technical properties, SF_6 has the disadvantage of having a very high global warming potential (GWP). It is the most potent greenhouse gas known.

Since the Kyoto Protocol of 1997, there have been discussions of measures that aim to reduce emissions of SF_6. One example is the voluntary commitment within the industry in Germany. On the European level, a ban on specific instances of use was discussed in 2014 in the context of the F-gas Regulation (EU, No. 517/2014), but ultimately rejected. The revision in 2020 provides for the examination of the availability of alternatives for SF_6 in specific switchgear in the medium-voltage range.

Against the backdrop of these climate policy-motivated efforts, Ecofys - a Navigant Company and ETH Zurich have been commissioned to identify and categorise technological alternatives and specific courses of action for replacing or reducing the use of SF_6 in newly constructed electrical equipment. The report focusses on switchgear, measuring transformers and electrical lines in the medium- (1 ≤ 52kV) and high-voltage (>52kV) in Germany.

Specifically, we tested the existing SF_6 alternatives regarding their implementability, advantages and limitations, as well as environmental impacts. The insights gained also help scientifically determine the climate protection potential of replacing SF_6 in medium- to high-voltage installations. For the potentials that have been identified for replacing SF_6, the possibilities as well as the limitations of a European withdrawal, the timeframe this would require, as well as proposals for accompanying measures should be worked out. In conclusion, we have inventoried, systematised and comparatively analysed instruments and measures for reducing the use of SF_6. During the study, our own research was linked with an intensive dialogue with manufacturers and users in the form of multiple interviews and expert workshops.

1.1 Findings and Conclusions: Status Quo

The highest SF_6 emissions in the distribution and transmission of electrical energy are emissions in the production of 'other electrical equipment' as well as operational emissions from high-voltage switchgear.

Existing emissions in the *high-voltage* (>52kV) sector exceed those in the medium-voltage sector many times over, although more SF_6 is installed in medium-voltage installations. Emissions during production are also high. The high reported emissions in the production of 'other equipment' (e.g. measuring transducers, bushings and capacitors) are not always traceable in detail. An accurate analysis and validation of the reported numbers is currently being done by the trade associations and the SF_6 work group.

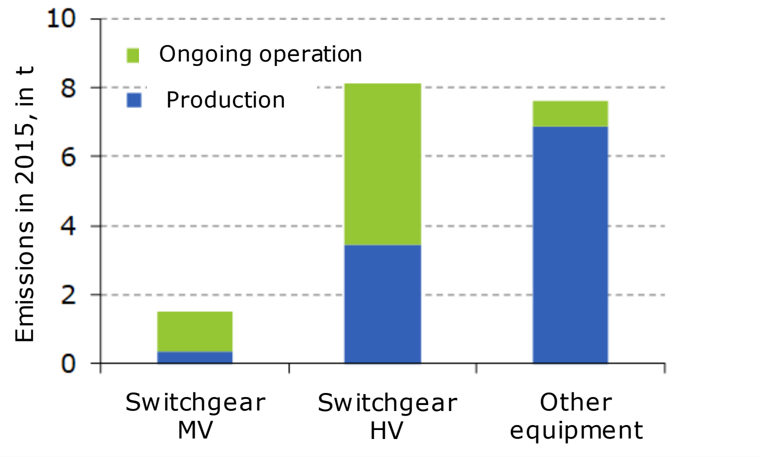

Figure Z1: SF_6 emissions from production and operation; emissions from disposal are negligible (2015). Source: Own research based on [SOLVAY et al., 2005; UBA, 2016]

In the medium-voltage, alternative solutions are available on the market, whereas in the high-voltage, further developments are needed.

In the medium-voltage range, there are established alternatives to SF_6. Some of these alternatives have been used successfully in commercial settings in other European countries for years. However, there are no alternatives that are equal to SF_6 in every technical respect, or that outmatch it. Depending on the area of application, air-insulated switchgear or switchgear with alternative insulation media like solids, liquids or alternative gases can be considered. In the medium-voltage range, vacuum circuit-breakers are the state-of-the-art switch medium.

In the high- and extra-high-voltage range, the selection of technically practical alternatives is more limited in terms of both insulations as well as switch media. In addition to using vacuums as switch media, practically the only considerable alternatives for insulation media or switch media are gases and gas mixtures.

Industry representatives assume that alternatives in the high-voltage range can reach a level of performance similar to SF_6 installations, though this will still require several years of development.

The F-gas Regulation and voluntary commitments have already resulted in significant reductions in SF_6 emissions.

Since initial implementation of the F-gas Regulation, the industry is working to reduce its SF_6 emissions in production processes, as well as in the utilisation phase in medium- and high-voltage. In Germany, this resulted in an industry-wide, voluntary self-commitment (starting in 1997, renewed in 2005) [SOLVAY et al., 2005]. This resulted in a reduction in SF_6 emissions related to electrical equipment from 50t of SF_6 in 1997 to 17t of SF_6 in 2015.

1.2 Findings and Conclusions: Further Developments

Further potentials for reduction are available, but exploiting them will require additional efforts.

Through ambitious efforts, it will also be possible in the future to achieve significant reductions in SF_6 emissions despite a rising number of installations. However, reduction potentials are more difficult to tap into than in the past, and they continue to depend heavily on voltage, use/type of electrical equipment and area of application.

- *High-voltage switchgear:* New installations already have a very high containment level. Product processes have already been greatly optimised. All possibilities for further reduction through improving operational processes must be considered. Substantial reduction in emissions will require the bold introduction of existing and future alternatives.
- *Medium-voltage switchgear:* Newly installed medium-voltage switchgear already features very low emissions rates (<0.1% p.a.). These leakage rates can be seen as technical feasibility limits. Therefore, further reduction potentials in medium-voltage installations can only be exploited if SF_6-free solutions are used increasingly for MV switchgear in the future. The actual reduction potential cannot be reliably quantified based on the model approach in the course of actual monitoring.
- *'Other Electrical Equipment':* The origin of the high absolute emissions in the production of 'other electrical equipment' has not been sufficiently explained. Existing reporting does not allow the precise sources of these emissions to be identified, nor does it point conclusively to the type of electrical equipment in question. The technical feasibility of alternatives or emission reductions thus remains unclear for now.
- *Decommissioning and Disposal:* The first major volumes of SF_6-containing electrical equipment are fast approaching the ends of their technical lifetimes. Therefore, decommissioning and disposal will be relevant topics for controlling emissions in the near future. General requirements are in place for the proper recycling of gases at the end of the equipment's lifetime. These are also part of voluntary commitments adopted by the industry. Considering the widely scattered locations of the electrical equipment and the non-registered allocation of electrical equipment, manufacturers and users, it remains to be seen whether all parties will carry out the processes with the necessary care.

Further, substantial reductions in emissions could ultimately depend fundamentally on a widespread switch to alternative technologies/gases. For such a change to take place, challenges for the reliability, safety and environmental soundness of new solutions must be carefully tested and comprehensively evaluated.

The industry requires regulatory and technical certainty

Pressure to further reduce the use of SF_6 brings with it adoption costs and a wide range of uncertainties for the industry. A reliable regulatory framework is a precondition for sustainable efforts.

Setting a mandatory target for further minimisation of the use of SF_6 is just as important for the industry as a consistent evaluation of the properties of relevant alternatives. In this area, there are still many uncertainties.

Especially the regulated network industry has a need for reliable statements on how the extra costs associated with alternatives are to be handled in the regulations.

Further development of voluntary commitments offers chances for continued progress

It is up to policy-makers to set the targets. The further reduction of emissions is increasingly difficult to realise. Mandatory reduction targets should therefore be regulated by the policy. The implementation of industry-wide targets however, can generally continue to stay with the industry itself; e.g. in the context of ongoing voluntary commitments.

SF_6 monitoring requires further development

If effective measures are to be established and carried out by policy-makers or the industry itself, it is necessary to know where emissions are occurring. Current methods and aggregation levels of SF_6 monitoring within the framework of voluntary commitments in the industry do not sufficiently allow for an independent evaluation and comparison of the performance levels achieved, or the identification of specific emissions sources. However, there are many difficulties associated with further improvements in monitoring. Three areas of monitoring deserve particular attention:

- *Emissions monitoring and reporting* (bottom-up), Possibility of differentiated identification of potential main emission sources (above-average emission rates);
- An *SF_6 register* in the form of a database on current oversight of the quantity, location, age and possibly the emissions rate of individual SF_6 switchgear.
- *Atmospheric emissions measurement* (top-down).

Considering the Replacement of Old Installations

The subject matter of the studies was new electrical equipment. Selectively replacing old installations can presumably reduce a large portion of operational emissions, both in the medium-voltage and high-voltage ranges. However, there are no simple, generic and reliable indicators (e.g. the age of the installation) through which the emission level of a specific switchgear can be discerned. The total potential, efficiency and effectiveness of these measures are therefore uncertain and difficult to assess in advance. Again, improved monitoring would help.

1.3 Recommended Actions

Policy and Regulatory Framework

- We recommend the specification of clear policy goals for further reduction in the use and emission of SF_6. Without setting clear policy goals, further reductions in SF_6 emissions by the industry will lag behind what is possible.
- Policy-makers must define the criteria for a consistent evaluation of the non-technical properties of the alternatives. These include the evaluation of climate relevance, health risks, consideration of additional costs in the incentives scheme and other similar topics.
- In our opinion, these clarifications should preferably be issued on the European level. National rules promise only limited efficiency and effectiveness.
- We consider normative specifications or financial incentives in favour of certain alternatives in individual applications to be less useful. An integrated specification of volumes for the industry as a whole (usage, emissions) is more effective, in our view. An expanded, voluntary commitment by the industry can serve as a suitable framework for this.
- Should a voluntary commitment fail to reach its goals, policy instruments that have deeper impacts must be considered and promptly worked out. If such courses of action are known, it increases the credibility and clout of the policy. It is part of the certainty that the industry demands.
- As a supplement to voluntary commitments adopted by the industry, specific instruments can be implemented. They allow 'low-hanging fruit' to be seized that would otherwise only be attainable with delays.
- One option would be to impose targeted sanctions on inadequate gas recovery and recycling. Effective sanctions must clearly exceed the costs of disposal.
- Furthermore, incentives systems can be useful in specific areas. However, these must be applied with moderation due to the risk of market distortion and deadweight effects.
  A: Supporting the replacement of leaky equipment.
  B: Supporting the market launch of alternatives by buffering against additional costs and risks.

Developing Voluntary Commitments Further

In this context, we consider the following aspects particularly worthy of attention:

- *Efforts to achieve ambitious targets must be shared fairly:* the efforts required to further reduce emissions will naturally increase as emissions decrease. Ongoing efforts by individual enterprises seeking to advance low-SF_6/SF_6-free technologies cannot count on a commercial base at this time. A clear code of conduct, combined with a consistent means of sharing the efforts within the industry, can strengthen security, even in a competitive playing field.
- *Greater efforts must be made to address 'other electrical equipment'.* It is indispensable for the industry to broaden its level of knowledge and develop a bold strategy. To a large extent, this aspect will affect only a small number of manufacturers. Even still, the distribution of efforts within the industry itself will be essential for facing the oncoming challenges.

- *Emissions - Not Emissions Rates:* The development of emissions in the field of medium-voltage installations shows that successes in reducing emissions rates are insufficient from an environmental policy perspective. In light of the immense increase in the number of installations, absolute emissions have once again been on the rise recently, despite the fact that emissions rates have been cut to the technical minimum. Therefore, it is reasonable to demand that targets be focussed on absolute emissions. This will stimulate the introduction of alternatives.
- *Substitution Road Map:* Ideally, the industry will work out a road map for further reduction in the use and emissions of SF_6, as well as the introduction of alternatives, and actively coordinate this with the policy level. We consider it expedient to quantify the interim steps along the way towards achieving the goal. This will support in evaluating the progress and increase the possibility of making targeted readjustments whenever difficulties occur, without the need for immediate action on the policy level. With all due reservations, such a road map would also provide an additional degree of certainty to all parties involved.
- *(Voluntary) Commitment by Users to Functional, Technology-Neutral Tendering:* In current practice, tendering documents for new electrical equipment regularly refer ‘out of habit’ to SF_6 installations. A requirement to generally avoid this specification in tendering and, in the future, to tender according to functionality would provide suppliers of alternative solutions with at least an equal competitive position, while also increasing product diversity.
- *Decommissioning and Disposal:* Proper recycling, reuse, disposal and destruction of SF_6 from decommissioned electrical equipment is already regulated in general. A detailed agreement on the processes and their oversight seems appropriate, in light of the volumes to be dealt with in the medium term. The handling of electrical equipment from which the gas currently cannot be recycled without excessive effort (e.g. measuring transducers) should be given particular attention at this time.
- *European Coordination:* An expansion of voluntary commitments to all of Europe would have an explicitly positive influence on the effectiveness of the measures. At the same time, we consider it appropriate to incrementally standardise individual points (selected topics in which it is possible to reach a consensus; individual Member States who are leading the way in specific areas). Otherwise, we are concerned that this coordination will take place at a very slow pace.

Further Development of SF_6 Monitoring, Emissions Oversight and Reporting

We consider it necessary to adjust the monitoring system in the following respects:

- *Make disaggregated data accessible to public authorities:* less aggregated data would help authorities to identify the worst emitters and to implement effective, efficient measures based on this, as well as to monitor progress towards reaching targets.

- *Standardise reporting systems on the EU level in all relevant respects:* the introduction of a coherent European monitoring system would be useful for comparison purposes and necessary in case of future EU-wide measures. Industry experts expect that the establishment of an EU-wide methodology will take at least a decade. However, this is no reason not to get started and to push for an incremental harmonisation of reporting practices, as needed.

- *Expanding the Responsibilities of Gas Producers and Suppliers:* Currently, gas producers do not report on SF_6 volumes. Involving them in reporting would simplify the entire process. The confidentiality and anonymisation of market-relevant data must indeed be given particular consideration, considering the limited number of market players. However, this could be maintained by limiting access to the data.

  The various import and export streams of European and non-European suppliers would, of course, also need to be depicted adequately. This is an additional argument in favour of a coordinated European approach.

- *Eliminate Lack of Clarity Surrounding the Term 'Other electrical equipment':* There are uncertainties regarding the distinctions between categories of electrical equipment, voltage levels and the definitions upon which monitoring is based. These should be eliminated to identify potential options for reduction.

- *Atmospheric Emissions Measurement:* We recommend, in addition to existing bottom-up inventorisation activities by industry associations, top-down oversight through atmospheric measurements and reverse modelling. Top-down analyses can supply very specific findings as to the regions and timeframes in which emissions originated. This may help to verify progress achieved in emissions reduction, to refine emissions modelling for the bottom-up inventory and to identify sources in need of attention. Even if some relevant emitters are missing or less reliably registered in the reporting (e.g. soundproof windows, military, non-EU countries), it would be useful to understand the volumes that are not measurable in order to bring top-down and bottom-up analyses closer in line with each other.

Developing and Introducing an SF_6 Register

- An SF_6 switchgear register in the form of a database to continually monitor the number, location, age and possibly the emission rate based on maintenance data would facilitate emissions reporting and unify bottom-up and top-down approaches. Such a register could be created for the high- and extra-high-voltage sector without excessive effort. In the medium-voltage sector, the pros and cons would need to be balanced:
- The precondition for data gathering is consensus on collection processes as well as on which data is to be collected and in which format. Such coordination among stakeholders would be a question of years rather than months, even on the national level. Individual companies have already introduced SF_6 registers in the course of their asset management activities, and have tested appropriate methods. Much can be learned from these companies as the discussion of a Germany- or EU-wide register continues. Furthermore, the experiences of EU Member States with regard to refrigerating plant registers can also be used as a reference.

Considering the Replacement of Old Installations

- If a significant portion of operational emissions can be reduced by selectively replacing old installations, incentives and socialisation of costs are justifiable.
- A clear inventorisation of existing installations, which also serves as a basis for reliably identifying worthwhile installations, is a precondition for implementing such measures. This can only be achieved by the industry itself. Sophisticating monitoring helps.

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2 Introduction and concerns

Background and importance of sulphur hexafluoride

In electrical energy technologies, the gas sulphur hexafluoride (SF_6) currently plays a key role as an insulating and arc-quenching medium, particularly in switchgear. Despite numerous advantages in terms of its technical properties, SF_6 has the disadvantage of a very high global warming potential (GWP) and toxic decomposition products resulting from switching operations. With a GWP_{100} of 23.500[1], it is the most potent greenhouse gas known. Furthermore with an atmospheric lifetime of about 3,200 years [2], SF_6 is extremely long-lasting [IPCC, 2013]. The categorisation of SF_6 as one of the six greenhouse gases in the Kyoto protocol of 1997 [UN, 2014b] has given rise to the discussion of emission-reduction measures, including in the gas's application as an insulating and arc-quenching medium in electrical equipment. In Germany, this resulted in an industry-wide, voluntary self-commitment (starting in 1997, renewed in 2005) [SOLVAY et al., 2005]. This commitment pursues the goal of reducing SF_6 emissions in the energy supply, for example, by implementing closed circuits, improved technologies, monitoring systems, shorter maintenance intervals, research for alternatives and employee training programmes.

At the same time, on the European level, a process of regulating the use of fluorinated greenhouse gases relevant to the climate (F-gases) was ongoing. As a result, in 2014, the European Union published a planned revision of its regulation on fluorinated greenhouse gases (EC No. 842/2008), to contribute to further reductions in the emission of F-gases. Specifically with regard to SF_6, at the initial stages of drafting, the European Parliament discussed a ban on certain instances of usage in the energy supply. However, such a ban was omitted from the completed regulation. Furthermore, there are no restrictions whatsoever on the use of SF_6 in electrical equipment [EU, 2014; Energy Networks Association Limited, 2013a, 2013b; T&D Europe, 2013a]. Ultimately, the current regulation on F-gases (EU No. 517/2014) provides for an assessment by the year 2020 of the availability of technically feasible, reliable and cost-effective SF_6-alternatives for new medium-voltage switchgear for secondary distribution (Article 21, section 4). It also provides for 'a review of the availability of technically feasible and cost-effective alternatives to products and equipment containing fluorinated greenhouse gases' (Article 21, section 2d) by the year 2022, which extends to all other instances of application in the energy supply.

Various studies and publications examining the possibilities and limitations of SF_6 substitutes have accompanied the sometimes controversial discussion process in recent years [T&D Europe, 2015b; Smeets et al., 2014; Benner et al., 2012; T&D Europe, 2013b]. With the presentation of alternative insulation gases and new SF_6-free equipment by individual manufacturers for selected applications, the discussion about the future use of SF_6 has recently taken on a new dynamic.

[1] This refers to the latest GWP value according to the Intergovernmental Panel on Climate Change (IPCC). Other studies still refer to earlier values, e.g. 22,800 or 23,900.

[2] A recent study calculates an atmospheric residence time of 850 years [Ray et al., 2017]. This results in a slight reduction of GWP (100) by approximately -4% (to a value of approximately 22,500), but a significant reduction for longer time horizons (-18% for GWP (500) and -32% for GWP (1,000)). In this report, however, we use the lifetime of 3,200 years, which is generally accepted by the UNFCCC.

This report supports the German Federal Environment Ministry (BMU) and Federal Environment Agency (UBA) in classifying current technological developments in the field of SF_6. The focus is on compiling an up-to-date overview of state-of-the-art technologies for installations with and without the use of SF_6. We also examine which coordinated policy-based, legal, regulatory and financial courses of action are able to achieve an effective reduction in the use of SF_6 in new installations and a reduction of SF_6 emissions in the manufacturing, use and disposal of new installations.

Focus of the study

This study focusses on medium- (MV) and high-voltage (HV) electrical equipment in which SF_6 is potentially used. Throughout the study, we use the following classification based on the IEC 62271-200 standard: Medium voltage refers to installations from 1kV up to and including 52kV, while high voltage refers to installations above 52kV. It must be noted that, in European standard practice in medium-voltage, electrical equipment in the 10kV to 36kV range is primarily used. This classification applies to rated voltage. Contrary to this, voltage on the grid level is defined by the nominal voltage, which is around 20% lower than rated voltage. For example, a 24kV switchgear is usually operated in a medium-voltage grid of 20kV.

Process

This report aims to show the current state regarding the use of SF_6 and SF_6-free alternatives in electrical equipment, and to provide a comparative analysis of potential regulatory mechanisms for replacing SF_6 in new installations and reducing SF_6 emissions. The focus is on classifying and evaluating the technical feasibility of SF_6-alternatives in the medium- and high-voltage levels.

The report is based on extensive research. We have incorporated findings from the following resources:

- The latest scientific publications by universities, research institutes, international technological/scientific organisations (Cigré, IEEE) and expert advice (Ecofys, CE Delft, Ökorecherche), as well as publicly available product sheets from manufacturers (Appendix 10.4) for the description and comparative evaluation of the technical properties of current technologies;

- National and international guidelines and technical standards, regulations and legal texts for the regulatory framework;

- 23 exploratory expert interviews and additional telephone interviews with manufacturers and users, as well as opinions from German and European trade associations, to gain a picture of the overall mood.

Furthermore, we held two technical workshops in 2017, in which we presented our interim results for discussion and tested the initial conclusions. The first technical workshop took place in March 2017. The results of the discussion are presented in Chapter 8. During the second workshop in Brussels in September 2017, instruments and concepts for reducing the use and emission of SF_6 were discussed. The outcomes of the discussion were incorporated into the design of the concept (Chapter 9).

Outline

The next two chapters (3 and 4) provide a general overview of the subject matter of the study. Chapter 3 discusses the significance of SF_6 for electrical equipment and the climate. Chapter 4 provides the technical foundation for understanding the use and function of electrical equipment that potentially uses SF_6. Furthermore, we categorise the equipment according to applications within the power system.

The two chapters after that specifically discuss the use of SF_6 and alternative technologies. Chapter 5 quantifies and categorizes the total number of installations. Chapter 6 compares the current state of SF_6-related technologies versus alternative technologies.

After the purely technical examination in the first part of the report, we describe the regulatory framework in chapter 7. This chapter provides an overview of the current framework and experiences in Europe.

Finally, in chapter 8 we sketch the current mood among manufacturers and users based on interviews and discussions. For this, we compare and contrast various positions on SF_6 and alternative solutions which we heard during the interviews and workshops.

In chapter 9, we draft possible instruments and measures for reducing the use and emission of SF_6. First, we categorise and evaluate different types of measures. Based on this, we compile and prioritise recommended actions for policy-makers as well as the industry.

3 Properties and climate-relevance of SF_6

Sulphur hexafluoride (SF_6) is an inorganic compound that is synthesised from elemental sulphur and fluorine. Under normal conditions, SF_6 is chemically inert, inflammable, non-toxic and gaseous at temperature above -64 °C [NIST, 2016]. Even at pressures applied in electrical equipment (up to 7 bar = 0.7 MPa), SF_6 occurs in a gaseous state, also at low temperatures, as shown by the vapour pressure curve (see Figure 2). SF_6 is five times heavier than air, is a good extinguishing agent, has good convective cooling properties, good sound insulation and a high electrical insulation capacity. The critical electric field strength (the field strength above which a gas loses its insulation capability) is approx. 88kV/cm at 1 bar, being three times as high as that of air (24kV/cm) [Küchler, 2009].

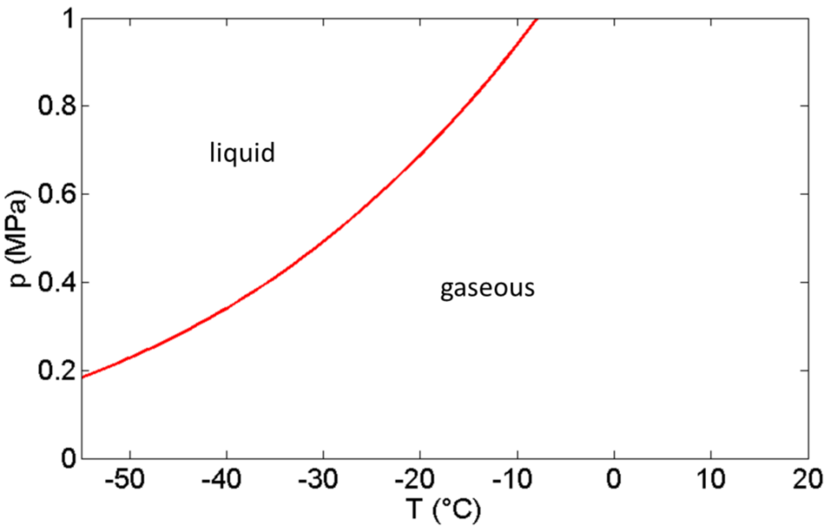

Figure 2: Vapour pressure curve of SF_6
Source: [Guder und Wagner, 2009]

The SF_6 molecule very effectively absorbs the reflected infrared radiation of the earth in a frequency range in which the atmosphere is relatively transparent. As such, the molecule contributes to the greenhouse effect and global warming. At the same time, with its lifetime of approx. 3,200 years, SF_6 is extremely long-lasting[3]. Figure 3 (left diagram) shows the ongoing global rise in the concentration of SF_6 due to global SF_6 emissions. Because of its long lifetime in the atmosphere, SF_6 accumulates irreversibly only on a time scale of millennia. Measurements of ice samples show that, in the pre-industrial period, SF_6 concentrations were less than they are today by three orders of magnitude. Since the 1990s, gas chromatography is used to measure atmospheric SF_6 concentrations at around 15 measurement stations operated under various measurement programmes [NOAA, 2014; Prinn et al., 2000]. In the first quarter of 2016, SF_6 concentrations reached approximately 9 parts per trillion (ppt). By comparison, the concentration of CO_2 is currently around 400 parts per million (ppm).

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[3] A recent study calculates an atmospheric lifetime of 850 years [Ray et al., 2017]. This results in a small reduction of GWP(100) by approximately -4% (to a value of approximately 22,500), but a significant reduction for longer time horizons (-18% for GWP(500) and -32% for GWP(1,000)). In this report, however, we use the lifetime of 3,200 years, which is generally accepted by the UNFCCC. (Ray et al., 2017)

The rise in atmospheric SF_6 is reflected directly in global SF_6 emissions in recent years, which are shown in Figure 3 (right). From the precise atmospheric measurements, regional SF_6 emissions can also be determined with the help of atmospheric transport models. SF_6 emissions calculated in this way for China [Fang et al., 2013b] were fairly consistent with those derived from inventorisation methods in [Fang et al., 2013a] and [EDGAR project team, 2010]. However, rising emissions in China account for only a portion of the global increase in emissions since 2000. It is likely that the total volume of SF_6 emissions reported in Annex I countries is significantly lower than the actual level of emissions [IPCC, 2013; Rigby et al., 2010; Levin et al., 2010]. At present, however, there are no measured values for SF_6 emissions (exceptions: Switzerland and the United Kingdom) among the individual Annex I countries (especially Germany).

In 2010, around 38 Gt of CO_2 [IPCC, 2013] and about 7,400 t of SF_6 [Rigby et al., 2014] were emitted. SF_6 emissions correspond to 0.17 Gt of CO_2 equivalent (CO_2-e), i.e. approx. 0.5% of global CO_2 emissions for 2010. However, in this comparison, the long residence time of SF_6 compared with CO_2 in the atmosphere has not been fully taken into account, since GWP is defined over a time horizon of 100 years. Therefore, because of the low decomposition rate, the long-term contribution to the greenhouse effect is significantly higher.

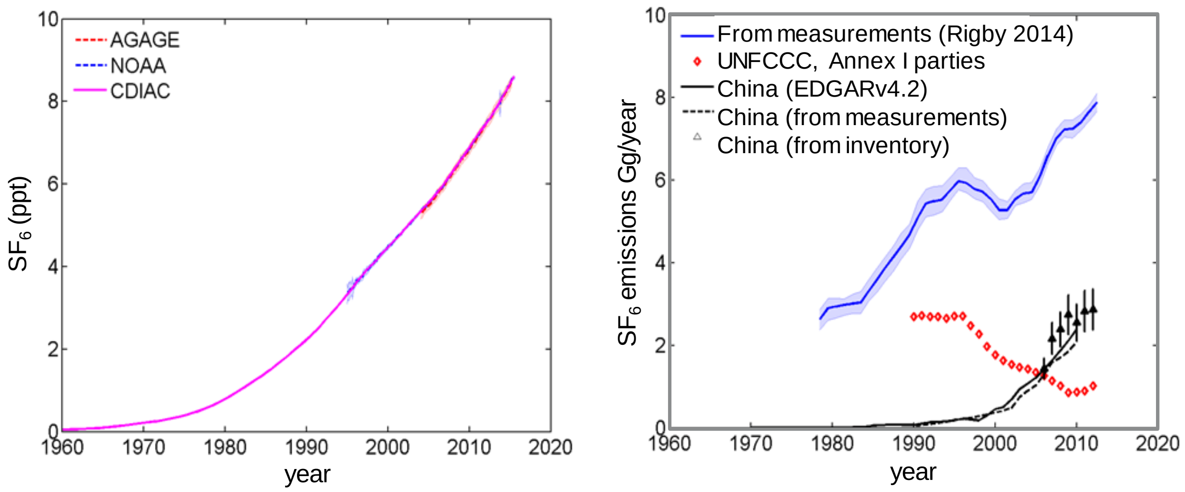

Figure 3: Left: Global mean value of atmospheric SF_6 concentration; right: Also shown are SF_6 emissions reported by Annex I parties from the UNFCCC database.

Because of the long life of SF_6, the annual rise of the SF_6 concentration is a direct measure of the annual SF_6 emissions. Source: Image on the left: AGAGE [Prinn et al., 2000], NOAA/ESRL [NOAA, 2014] and CDIAC [CDIAC, 2015]. Image on the right: For China, the emission data are shown from the EDGARv4.2 database [EDGAR project team, 2010] as well as estimations from measurements [Rigby et al., 2014; Fang et al., 2013b].

The physical and chemical properties of SF_6 mentioned in the introduction are advantageous in various technical applications. SF_6 is used in various industrial sectors, and, every year, several thousand tons are produced [Smythe, 2000]. Globally as well as in Germany, the electrical industry is currently by far the greatest SF_6 consumer (about 85%, see Figure 4). Furthermore, SF_6 is used in the magnesium and aluminium industries as well as in the semiconductor industry. The consumption quantities of these applications combined represent less than 10% of the total consumption volume of SF_6 reported in Germany (see Figure 4). In the past, SF_6 was also used as fill gas in vehicle tyres, sports shoes and sound-proof windows.

Such usage has been banned in the EU, and active research for alternative substances is currently in progress in most other sectors [Statistisches Bundesamt, 2015]. SF_6 is also used in military systems (radar, Mark 50 torpedo) and in the medical and radiation industries, as well as in voltage stabilisers in electron microscopes and x-ray machines. These areas of application are not listed in Figure 4.

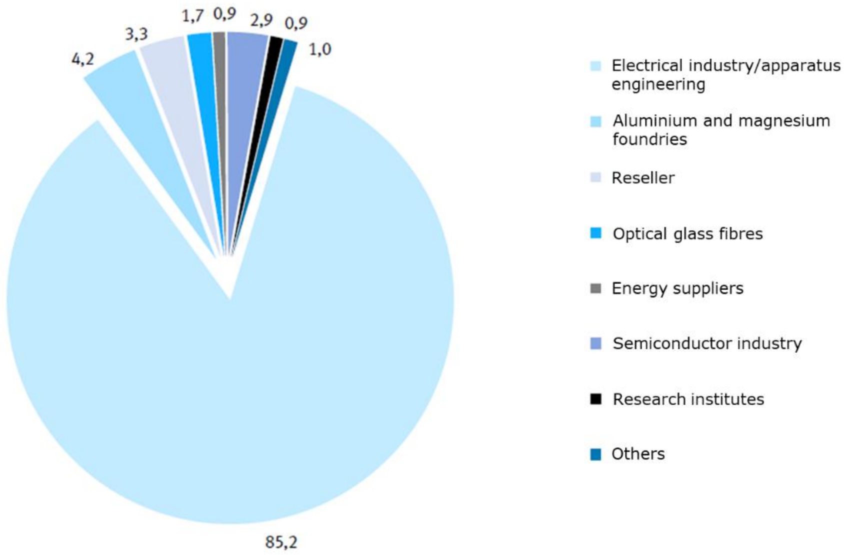

Figure 4: SF_6 consumer groups according to usage areas in % in 2015[4]
Source: [DESTATIS, 2016]

The electricity industry is the largest user of SF_6. However, in terms of atmospheric impact, emissions are key. Figure 5 shows SF_6 emissions per area of application throughout the lifetime of the products. Soundproof windows are by far the largest emitters of SF_6. However, the use of SF_6 in soundproof windows has been greatly reduced since the 1990s and has been banned since 2006. The reported emissions are based on projections that assume that 1% of the SF_6 stored in the windows is emitted each year and fully enters the atmosphere after a lifetime (25 years) of the window (i.e. the remaining amount of SF_6 in the window at the time of disposal equals 78% of the original amount). Therefore, SF_6 emissions from soundproof windows (estimated at 115 t in 2015, equalling 2.6 million t of CO_2-e) will be almost completely eliminated from the equation by 2030, and will reach their peak at around 2019.

[4] 'Others' include the areas of application: manufacturing of soundproof windows, automotive garages and the tyre industry, flight operations (radar), solar technology and miscellaneous DESTATIS, 2016.

Currently, electrical equipment is the second largest emitter, producing 17t of SF_6 emissions each year (or 0.4 million t of CO_2-e). This number includes emissions from the production, use and disposal of electrical equipment, such as high- and medium-voltage switchgear and 'other equipment' such as measuring transformers and capacitors [UNFCCC, 2016].

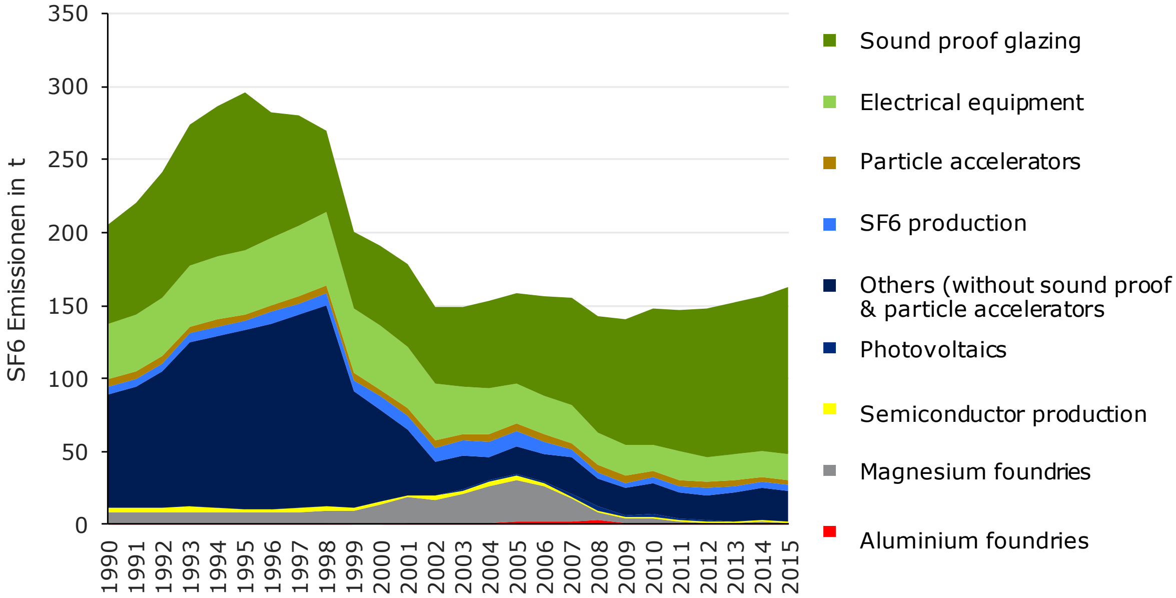

Figure 5: SF_6 emissions in tonnes per area of application throughout the entire lifetime of products in Germany Source: [UNFCCC, 2016]

The largest portion of SF_6 emissions are generated during the production of electrical equipment. During the use of electrical equipment, SF_6 is emitted in small amounts or with a delay through leaks, losses during maintenance or malfunctions. Leakage rates depend on the production method of the enclosure, quality of the seals and the age of the electrical equipment. Emissions during disposal still account for a very small share of the total amount of emissions, as only a small amount of equipment using SF_6 has reached the end of its technical lifetime, which is around 40 years. Chapter 5 describes the emissions in production and operation in detail.

4 Fundamentals of electrical equipment and its technical properties

For the safe and efficient operation of the European power system, a wide range of electrical equipment is in use. In the context of this study, the focus lies on switchgear, instrument transformers and power lines in which SF_6 is potentially used as insulator or arc-quenching medium. Gas-insulated transformers fall outside the focus, as they are hardly used in Europe.

In the sections below, we describe the technical features and functions of the electrical equipment and components in use. Because fundamental technical requirements and design features are based on the selected operating voltage of the electrical equipment and its components, we use voltage levels as the distinguishing criterion, starting in section 4.3. Special fields of applications have specific requirements for switchgear and ‘other electrical equipment’. We define these requirements in section 4.4.

General requirements set the framework for the properties of electrical equipment

An essential criterion when designing electrical equipment is a compact design. In urban areas, the installation of electrical equipment often depends upon space-saving construction. Furthermore, cost constraints are a factor, especially at the lower voltage levels. This applies equally to the installation costs and the construction costs, which are defined not least of all by the dimensions of the installation. Finally, the necessary power requirements (rated voltage and current) for each type of application dictate fundamental specifications for how the electrical equipment is designed.

4.1 Functions of insulating and arc-quenching media

Figure 6: contains a schematic, technically simplified depiction of the three essential functions of insulating and arc-quenching media:

- Cooling
- Extinguishing
- Insulation

This is an important distinction to clearly separate the various areas of application of SF_6 alternatives for certain components in the following chapters.

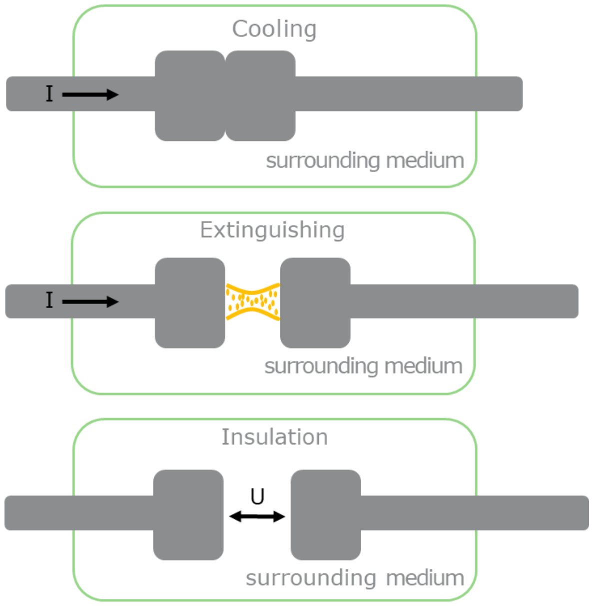

Figure 6: Simplified depiction of the three positions of a switch and the functions of insulating and arc-quenching media

1) In the closed position, the operating current (I) generates heat, which is dissipated by the surrounding medium.

2) Opening creates an electric arc, which is extinguished.

3) In the open position, the operating voltage (U) is held within the insulation gap.

Source: Own research

- ***Cooling at normal load:*** In the closed state, the heat put off by the current-carrying conductor must be effectively dissipated outwards to limit thermal wear on the components. In gases, a high density, a high heat-transfer capacity (heat conduction, -radiation and -convection) and a low viscosity increase the cooling through convection.

- ***Extinguishing electric arcs during switching processes***: When the switch is opened, the electric arc that occurs must be extinguished within fractions of a second. The switch design and the properties of the hot gas or plasma determine the switch's performance. Switching in SF_6 may result in toxic by-products such as SF_4, SF_5, SF_2H_{10}, SO_2 and HF.

- ***Insulation of high electric field strengths***: When the switch is open, the switching path or conductor must be insulated against the present operating voltage and the transient overvoltage. When a gas is used as the insulator, the higher the gas pressure and distance between the current-carrying and grounded parts, the better the insulation. At constant pressure and distance, the so-called critical electric field strength is the factor that quantifies the insulation capacity of a specific gas. In addition to a high critical electric field strength, a low boiling point of the gas is a necessary criterion, because condensation at low temperatures reduces the gas pressure and hence the insulation capacity.

The insulation of current-carrying parts from grounded parts and the dissipation of heat from current-carrying parts are necessary in all of the electrical equipment considered in this study. Extinguishing characteristics are only relevant when the components serve a switching function, such as circuit-breakers and load switches.

4.2 General features of insulating and arc-quenching media

The three functions determine the various physical requirements for the enclosing medium. Switching and insulation media available today can be classified as follows, according to their physical state during normal operation:

- Vacuum
- Gases or gas mixtures (e.g. SF_6, SF_6/N_2, SF_6/CF_4, air)
- Liquids (e.g. ester or oil)
- Solids (e.g. polyethylene)

In thermodynamic terms, vacuums used as insulation media can be considered as heavily pressure-reduced gases. Yet, as a dielectric material, a vacuum is fundamentally different from a gas and is therefore considered separately in the literature. The various insulation media are not only used separately, but are also combined with one another in many types of electrical equipment. Examples are cellulose board barriers in transformer oil, epoxy resin in gas-insulated switchgear or support insulators in a gas-insulated lines (GIL). Historically, many different insulation and extinguishing media have been used in MV and HV applications. There are multiple criteria for choosing the best insulating and arc-quenching medium, depending on the specific application. Certain compromises must always be made with respect to weight, size, heat transfer properties, lifetime, flexibility, production costs, maintenance costs, environmental influences, health risks and the personal safety.

For low electric field strengths, atmospheric air is technically the simplest and most economical insulation medium and is used in overhead lines and air-insulated switchgear (AIS). Increasing the gas pressure considerably improves the insulation and extinguishing properties of any gas, but requires a gas-tight, stable enclosure for the current-carrying parts. This concept of a gas-insulated switchgear (GIS) also partitions off any harmful environmental influences. In the 1930s, synthetic compounds were used instead of air for the first time, which contained atoms of electronegative elements like chlorine and/or fluorine. Such gases, including SF_6, enabled significant improvements in insulation and switching properties. Since the 1970s, SF_6 has been used increasingly as a switching gas. To enable the use of gases at very low temperatures (e.g. - 50 °C), mixtures such as SF_6/N_2 or SF_6/CF_4 are also used. More than 100 AIS circuit-breakers with an SF_6/CF_4 mixture have been in operation in Canada since at least the year 2000 [Middleton, 2000]. Pure CO_2 has also been used for several years as an extinguishing gas in circuit-breakers. Recently, a perfluorinated ketone (C_5-PFK) and a perfluorinated nitrile (C_4-PFN) have been used as admixtures to CO_2, N_2 or O_2 in insulation and switching applications. Due to their chemical properties, they are suitable for the use as insulating gas and have a positive influence on the withstand of transient recovery voltage and the recovery of the switching gap isolation, which is required for a successful switching process. Since C_5-PFK[5] and C_4-PFN as pure gases liquefy even at relatively low fill pressures and high temperatures (compared to SF_6), these substances are added in small amounts to gases such as CO_2, N_2 or O_2. Another advantage of adding O_2 is that is reduces soot formation and deposits.

Using a vacuum for insulation is logical, because vacuum does not contain potentially conducting material. However, the production and use of vacuum-tight parts for circuit-breakers only became possible in the 1960s. Today, vacuum circuit-breakers dominate in MV applications. They have also been used occasionally in HV applications for several

[5] At room temperature and normal pressure, C_5-PFK is liquid, not a gas.

years. However, vacuum is not used only for insulation, because it would be very intensive technically to ensure the vacuum-tightness of larger electrical equipment, such as a GIS.

Solid insulators include epoxy resin, polyethylene, laminated paper, silicone and porcelain. A basic disadvantage of solid insulators compared with vacuums, gases and liquids is the irreversible damage caused to the insulation by partial discharges. Solid-state circuit-breakers use semiconductor elements, have a relatively high conduction loss and short lifetime compared with vacuum circuit-breakers, and have thus far not been used in AC switches. Solid insulators are widely used in MV switchgear. A 'classic' solid insulator is usually a combination of solid material and air, in which a relatively thin solid insulator displaces the electrical field into the adjacent air. Additionally, this bounding surface of the solid insulator can be coated with a conductive material and grounded. This prevents the surrounding air from becoming stressed with an electric field, and only the solid is exposed to voltage. This is known as a 'shielded' solid insulation system.

Production processes for solid-insulated components are more intensive than those for gas- and liquid-insulated systems, and require greater precision. Even the smallest air inclusions must be avoided by all means, as these accelerate ageing and will cause the electrical equipment to malfunction within several months to years of operation. Thermal expansion of the components must also be taken into consideration. In the early days of solid insulation systems, customers occasionally encountered operational problems due to manufacturing defects. Meanwhile, production processes have greatly improved among established manufacturers. To achieve this, x-ray measurements, type tests with temperature cycles and vacuum potting processes were introduced, among other techniques. However, compared with gaseous and liquid substances, processing solids is still more intensive.

Liquid insulators are primarily mineral oils, silicone oils and natural and synthetic esters. Their advantages are their good impregnating properties and effective heat transport through convection. At the beginning of the twentieth century, water was used as the arc-quenching medium. While distilled water has a relatively high impulse dielectric strength, it is also relatively highly conductive, so it is not used in electrical equipment. Furthermore, when chosen properly, oils can be used throughout a broader range of temperatures. Mineral oil was also used as an extinguishing medium in circuit-breakers until the 1970s, when it began to be replaced by SF_6 and vacuum circuit-breakers. Today, oils and esters are used mainly in transformers and occasionally in MV switchgear. Disadvantages of mineral oils are their high flammability and the environmental problems associated with oil leaks. However, synthetic oils and esters can greatly reduce flammability and the negative impacts on the environment.

Insulation

All insulation media possess electric strengths which enable high operating voltages in components at increasing insulation distances. Electric strength is sensitive to various parameters, such as the composition, production processes, pollution or ageing of the material as well as the homogeneity of the electrical field and the applied voltage wave shape (DC, AC, switching surge or lightning surge). With any insulation medium, as the insulation distance increases, so does the breakdown voltage and thus the maximum possible operating voltage, as depicted in Figure 7. This explains why the size of the equipment increases along with the operating voltage.

Gases nearly linearly increase over a wide range, while the breakdown voltage in solids, liquids and vacuum does not increase linearly with the insulation distance, but saturates as the insulation distance increases.

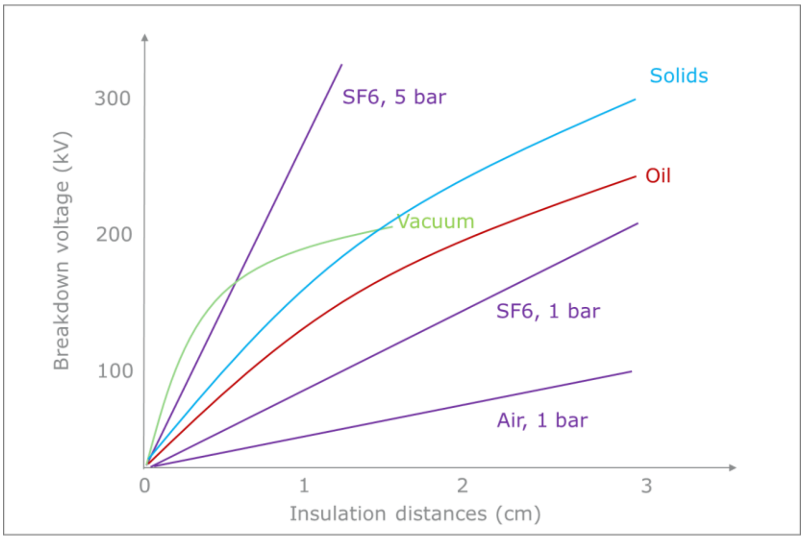

Figure 7: Qualitative comparison of different insulation media: breakdown voltage depending upon the typical dimensions of an electrical device
Source: [Müller, 2009; Kahle, 1988]

The electric strength of a gas strongly depends on its components and the pressure. As such, the critical field strength of SF_6 is three times that of air. Since the breakdown voltage of a gas generally increases linearly in proportion to the insulation distance and the pressure throughout the technically relevant pressure range, a higher gas pressure and greater insulation distances present a possibility for increasing the electric strength of a system. The increase as well as the pressure rise (increasing pressure difference between the encapsulated gas volume and the ambient air requires thicker vessel walls) results in higher material consumption. Therefore, when designing gas-insulated equipment, it is necessary to consider the dimensions and operating pressure in favour of maximal electric strength and minimal material costs. Pressures just above 1 bar are usually used in MV electrical equipment, while pressures of up to about 8 bar are used in HV. Much higher pressures would also be possible in principle for gases like N_2 or O_2. For SF_6 and other synthetic gases or gas mixtures, higher pressures are restricted mainly by the liquefaction of gases at high pressures and low temperatures, which is determined by the gas's vapour pressure curve (see Figure 2 for SF_6).

Breakdown in vacuum systems is determined by a surface effect. Thus, the electric strength depends mainly on the shape and the material of the electrodes. In contrast to gases, breakdown voltage in vacuum systems does not increase linearly with the insulation distance (see Figure 7). In medium voltage (≤ 52kV), short insulation distances are sufficient. To achieve high breakdown voltages, either the insulation distance must be made longer or multiple units arranged in series must be used. This design leads to larger dimensions and higher production costs. Both also result in higher energy needs for the opening mechanism (usually spring-loaded accumulators) of the switch. Ensuring even voltage distribution between the units arranged in a series is difficult, especially in case of high short-circuit currents.

For this reason, vacuum is used today in MV circuit-breakers and in AIS in the HV up to around 145kV. HV circuit-breakers for operating voltages above 145kV are possible in principle and are subject of research and development [Smeets et al., 2014].

For liquids and, especially, for solids, the likelihood of defects in the insulation system/material which initiate a breakdown increases with increasing insulation volume. Hence the critical field strength decreases with increasing insulation distance. This results in the 'bending' of the breakdown voltage. In solids, it can lead to defects such as small spherical air voids, gaps in the stratification of insulating materials and cracks due to long-term thermal and mechanical stress. Due to the effect of 'field displacement', the electric field strength in such air inclusions is greatly increased compared to the field strength in the solid material. Since the electric strength of gases is normally much lower than that of solid materials, it can lead to partial discharges in the air voids. Although this does not directly lead to a failure of the insulation overall, it greatly accelerates the degradation of the solid material. Measurements of partial discharges are an important testing method for detecting such defects especially after production and after long-term operation. There are also 'online monitoring' methods that allow partial discharges to be measured during operation. Despite significant improvements in manufacturing processes over recent years, partial discharge measurements remain an important test method for solid insulations.

Heat transport

Media that insulate current-carrying conductors, must not only have a high electric strength, but should also effectively dissipate the heat of the conductor to the environment (see section 4.1) to prevent damage to the equipment. Among heat dissipation mechanisms, there are fundamental differences between the insulation materials. Whereas cooling occurs through heat conduction and heat radiation in gaseous, liquid and solid media, convection is impossible in solids. Heat transport via heat conduction in gases is about one order of magnitude less than in liquids and two orders of magnitude less than in solids. However, heat transport via convection in gases and liquids is proportional to the characteristic length of the flow and hence proportional to the insulation distance. This results in increasing convection cooling with increasing insulation distance. Therefore, convection is the predominant cooling mechanism for technically relevant dimensions of insulation distances in HV applications (SF_6 in a GIS/GIL, oil in a transformer). This is the basis for the high transmission powers and the overload capacity of SF_6 or fluid-insulated busbars. In contrast, in solid insulators, heat conductivity decreases as insulation volume increases, and the temperature difference between the inner conductor and the exterior increases along with the risk of overheating and stress cracks in the insulation. In both liquids and solids, in addition to the heating of the current-carrying conductor, so-called dielectric heating also occurs, which is caused by the conductivity (in AC and DC systems) and the polarisation of the insulation (only in AC systems). The presence of AC voltage forces a periodically changing polarisation of the material, a process associated with energy loss and hence heating of the material. Dielectric heating normally increases additionally along with temperature. Mainly with solids (due to the absence of convective cooling and the relatively high dielectric losses) this additional increase in heating leads to the thermal runaway. Therefore, completely solid insulation is used primarily in MV applications. For HV applications, however, completely solid insulation (e.g. an HV busbar) is considered technically difficult. As such, solids are used only as part of an insulation (e.g. supports).

Arc-quenching

Arc-quenching media require high electrical insulation capacity, effective heat transfer, quick arc-quenching and long-term stability of the gas. A distinction is made between load-switching and circuit-breaking.

Circuit-breaking

In MV circuit-breakers, mainly vacuum circuit-breakers are used as the arc-quenching medium because of their high reliability and switching performance (see section 5.1). During the switching process, a metal-vapour electric arc occurs in vacuum circuit-breakers, which is extinguished very quickly due to the strong diffusion, thus enabling rapid switching. The number of possible switching actions (multiple tens of thousands) within the entire service life of vacuum circuit-breakers is also higher than that of SF_6 circuit-breakers, due to the higher stability of the switch contacts, lower electric arc voltages and faster arc-quenching. The switching of high currents is not a problem for vacuum circuit-breakers; however, the high operating currents are technically challenging because of heat development on the contact surfaces and limited heat transfer. In SF_6 circuit-breakers, it is easier to reach high operating currents, since, unlike with vacuum circuit-breakers, heat transfer occurs not only via the conductor, but also in all directions as well as through convection.

Load-switching

SF_6 is used in most load switches and load-break switches. SF_6 load-break switches, which are used predominantly in MV switchgear (with blade-contact or puffer principle), are technically simpler and significantly less expensive than vacuum circuit-breakers.

Specifications

The insulation, heat transfer and switching properties of the individual medium decisively determines the area of application for the electrical equipment. At the same time, maximum voltages and currents under normal operation and under transient conditions are of critical importance. The most important parameters are:

- Rated voltage and rated current: the maximum operating voltage and current until which the device is intended to be used;

- Breaking current (for switches): maximum current, for which a switch is specified when breaking the current.

Other parameters are defined by certain standards that products on the market must meet. For this reason, standards differentiate between different voltage waveforms and frequently between different components. In Europe, IEC standards are the usual point of reference (similar to ANSI standards in North America). In special applications, usually when very high reliability is required, the demands users place on manufacturers occasionally exceed these standards. Examples of this include lower minimal operating temperatures, higher current-carrying capacity or better switching properties. Some of the typical parameters defined by standards are:

- Rated short-duration power frequency withstand voltage: The effective value of AC voltage which the equipment's insulation must withstand during a period of one minute.
- Rated lightning impulse withstand voltage: Peak value of a standard impulse voltage wave which the equipment's insulation must withstand. This parameter's value must be high so the equipment can withstand short surges that may be caused by a lightning strike.
- Rated switching impulse voltage: Peak value of a standard surge voltage wave which the insulation of rated-voltage equipment must withstand. This parameter's value must be high so the equipment can withstand pulse-shaped surges caused by switching processes in the grid.
- Rated short-time withstand current: Current which a device can conduct during a defined short time.

Switchgear classifications and terminology

Among switchgear, a distinction is commonly made between indoor and outdoor applications, medium and high voltage or the various constructions and/or designs of the installations. Figure 8 illustrates these subdivisions and explains the most important switchgear design types. The glossary of this report (Appendix 10.1) also provides detailed definitions of the terminology used.

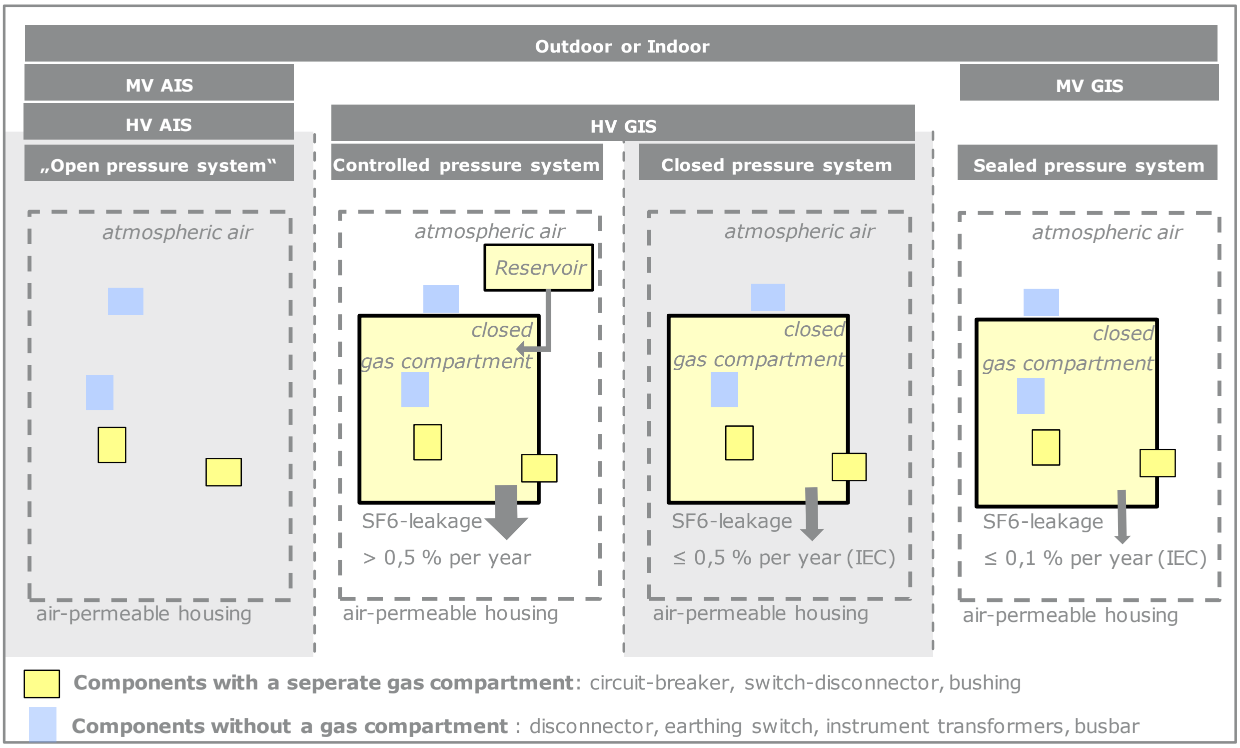

Figure 8: Schematic overview of the subdivision of modern switchgear based on construction
Source: Own research

All modern MV switchgear (air-, gas-, fluid- and solid-insulated) include a grounded enclosure (see, e.g., Figure 9), which contains the components listed in Table 4. This design is referred to as 'metal-enclosed' or 'metal-clad'. The enclosure can be touched, which means MV switchgear can be operated safely in confined spaces where a high level of personal safety is required. HV AIS are open, outdoor applications (see Figure 14, left) and do not have an enclosure as such (for illustration purposes, the fence around the open-air installation can be seen as an 'enclosure'). An installation is considered an AIS if all its components are situated in atmospheric air and thus directly exposed to environmental influences. In a GIS, on the other hand, all switching components are separated in a closed, air-tight gas compartment. Meanwhile, the absolute gas pressure of an MV-GIS is slightly increased (approx. 1.3–1.8 bar) and that of an HV-GIS is significantly increased (up to approx. 8 bar). Thus, the gas pressure and consequently the electric strength[6] of an AIS installed in high altitudes differs from that of an AIS installed at sea level, while a GIS displays the same electric strength regardless of air pressure. Furthermore, GIS installations ensure protection against various environmental influences (dust, tree roots, snakes, etc.). In GIS as well as in AIS, individual components, such as circuit-breakers can have a separate gas compartment (e.g. filled with SF_6).

GIS are subdivided into three different designs: controlled, closed and sealed pressure systems (acc. IEC-62271-1 standard). In controlled and closed pressure systems, gas escapes with leakage rates (a standardised value is not defined), which require a regular refilling of the installation. These systems have not been used in Germany for many years. A small part of the HV-GIS inventory is still designed as a controlled pressure system. However, because to its age, this generation of installations is due for replacement. Closed pressure systems only need a refilling in case of maintenance. HV-GIS are usually designed as closed pressure systems. The standardised values for SF_6 and SF_6 mixtures according to IEC-62271-1 are 0.5% and 1% per year. The interval between two refills must be at least 10 years. Closed pressure systems are usually only refilled if this is detected during the course of maintenance (every 10 years or more) or indicated by a warning signal from the gas compartment monitoring system. Most of today's gas-, fluid- and solid-insulated MV switchgear is equivalent to sealed pressure systems. These require no additional gas supply throughout their expected service life. A leakage rate of approximately 0.1% per year can fulfil a typical service life of up to 40 years. To distinguish between various technologies in this report, the term MV-GIS is only used for switchgear containing SF_6 or alternative gases (see Table 11). In particular, systems that use dry air at increased pressure as an insulating medium are also referred to as GIS. The labelling of switchgear as 'indoor' or 'outdoor' is primarily linked to the equipment's minimum operating temperature, below which operation is no longer possible. IEC 62271 requires a minimum operating temperature of -5 °C or indoor installations and -25 °C for outdoor installations, although users often demand minimum operating temperatures as low as -15 °C for indoor installations.

4.3 Electrical equipment classified by voltage level

In Germany as well as in Europe, the current power system is divided into two system levels with multiple voltage levels. The transmission grid transports power in the extra-high voltage level across long distances. The distribution grids transfer the energy to consumers and help in 'collecting' the energy from decentralised production plants.

[6] A pressure difference of approx. 20% (estimated using the formula for barometric correction for elevation) exists between AIS installations at sea level and those at high elevations (2,000m above sea level). Electric strength usually scales linearly with air pressure, which means it also decreases by 20%.

Distribution grids themselves are subdivided into high-voltage grids for trans-regional distribution, medium-voltage grids for regional distribution and low-voltage grids for local distribution.

The focus of the study is on **high and extra-high voltage (> 52kV) as well as medium voltage (≤ 52kV).** Because of the low field strengths found in low voltage applications, SF_6 or other gases are generally not used in low-voltage electrical equipment. Therefore, it is unnecessary to include low-voltage installations in this report.

Historically, there has been great variety in Europe in terms of assigning rated voltages to specific voltage levels. This is particularly true for the distinction between medium voltage and high voltage. There is no universally accepted standard. In the present report, we follow a classification system based on the IEC 62271-200 standard, which is oriented by the rated voltage of the electrical equipment (see Table 1). This classification is also consistent with the majority of electrical power systems operating in Europe [Eurelectric, 2013].

A distinction must be made between the classification of electrical equipment and the classification of grid levels. Generally, grid levels are defined by their nominal voltage and a distinction is made between high and extra-high voltage. However, in this report, we have chosen to classify based on electrical equipment. Based on this classification, high- and extra-high voltage are defined as one category (> 52kV), (see Table 1).

The following example illustrates the differentiated classification with regard to nominal and rated voltage: Based on its rated voltage of 24kV, a switchgear is installed in a medium-voltage grid with 20kV (rated voltage).

Table 1: Classification of voltage levels used for electrical equipment and grid levels
Source: Own research

Electrical equipment classification		Grid level classification	
Voltage level	**Rated voltage**	**Voltage level**	**Nominal voltage**
Medium voltage	> 1kV ≤ 52kV	Medium voltage	10, 20, 30, 35kV
High voltage	> 52kV	High voltage	> 52kV ≤ 150kV
		Extra-high voltage	> 150kV

Because essential technical requirements and design aspects are determined by the selected operating voltage of the switchgear and its components, in this report we use the voltage level, defined by the rated voltage of electrical equipment, as the distinguishing feature throughout all sections.

Table 2 gives an overview of the relevant electrical equipment for each voltage level.

Table 2: Overview of electrical equipment and components under review
Source: Own research

Voltage level	Electrical equipment	Components under review
Medium voltage (MV)	Switchgear for primary and secondary distribution	• Circuit-breakers • Disconnecting switches • Load switches • Load-break switches • Instrument transformers • Bushings
	Switchgear for generators	• Generator circuit-breakers
High voltage (HV)	Switchgear	• Circuit-breakers • Disconnecting switches • Instrument transformers • Bushings
	Lines	• Gas-insulated lines

4.3.1 Medium-voltage electrical equipment

Below is a description of electrical equipment reviewed for the medium-voltage (> 1kV and ≤ 52kV) regarding function and design. These are found especially in transformer stations, local grid stations or for connecting wind or (large-scale) solar installations. Section 4.4 contains an overview of application scenarios.

Switchgear for primary and secondary distribution

A switchgear generally includes switching devices for disconnecting non-energised equipment for repair and service work and for switching equipment on and off in regular operation or in case of outages. Components under review within this study are listed in Table 2. Furthermore, a switchgear also includes control, measurement and safety devices.

There are different forms of medium-voltage switchgear:

- switchgear for primary distribution (e.g. as part of transformer stations where high voltage is transformed to medium voltage, as well as in industrial and infrastructural applications), and
- switchgear for secondary distribution (distribution at medium voltage or as part of transformer stations where medium voltage is transformed to low voltage).

Figure 9: Typical medium-voltage switchgear in primary distribution (left) and secondary distribution (right) in size comparison (rated voltage: 24kV)
Source: Own research based on manufacturer diagrams (see product sheets)

Switchgear for primary distribution (see Figure 10; orange) at the medium-voltage interface of high voltage to medium voltage transformer stations, in industrial grids, in power stations or main power supplies for large building complexes and/or infrastructure facilities. The components of medium-voltage installations for primary distribution are designed to conduct operating currents of up to several thousand amperes and to control and switch fault currents. Figure 11 shows such a medium-voltage gas-insulated switchgear (GIS) for primary distribution. Table 3 on the next page shows the components typically used in switchgear.

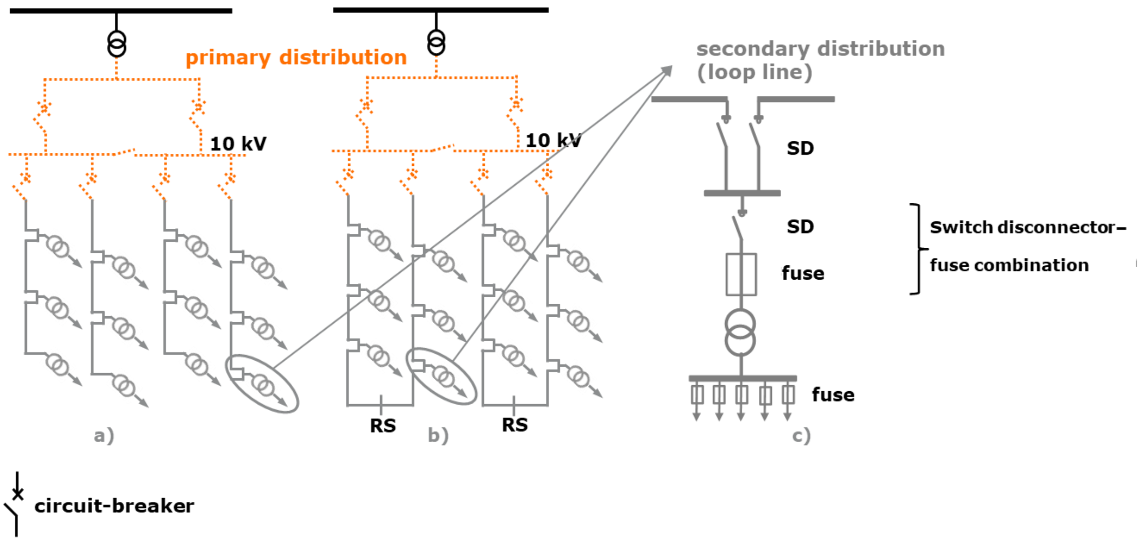

Figure 10: Typical grid topology for primary (orange) and secondary (grey) distribution

- **a) Radial grid with stubs**
- **b) Ring grid with disconnection points**
- **c) Illustration of grid topology of a switchgear for secondary distribution.**

RDP: Ring disconnection point; LBS: Load-break switch

Source: Own research based on [Schwab, 2009]

Switchgear for secondary distribution (see Figure 10; dark grey) distributes electrical energy either at the medium-voltage level or are situated at the interface from medium to low voltage. They are mainly installed in local grid stations of power supply companies and municipalities, but also in significant quantities in infrastructure and at small companies (see chapter 5). Secondary distribution mainly uses pure switchgear with load switches, supplemented by combined load-break/circuit-breaker fields and/or fused load-breaks. So-called 'ring main units' (RMU) are the most common sub-form of medium-voltage switchgear for secondary distribution. RMUs are compact switchgear that enable power distribution within the local grid territory. They usually consist of three functional units: the incoming cable, outgoing cable and outgoing transformer bays. Depending on their design, they can be modularly expanded (see also application scenario 1: local grid stations). The incoming and outgoing cable bays require load-break switches simply for switching nominal currents, since normally no short-circuit currents are switched (these are usually switched at the switchgear for primary distribution). In the outgoing transformer bay, a *fused load-break* (also known as a '*switch-fuse combination*') or, alternatively, a circuit-breaker is used. The rated operating voltage of medium-voltage switchgear for secondary distribution typically has a maximum of 24kV, and the rated operating current has a maximum 630A.

Figure 11: Typical medium-voltage switchgear (operating voltage: 24kV) (not true to scale)
From left to right: Air-insulated switchgear (AIS) for primary distribution, gas-insulated switchgear (GIS) for primary distribution, gas-insulated switchgear (GIS) for secondary distribution (ring cable), cross-section of a gas-insulated switchgear (GIS) for primary distribution (SF_6 gas volume in green)
Source: Product sheets (see Appendix)

Components of switchgear (switching devices):

Switchgear consist of various switching devices. Their actual configuration depends on the application and specific requirements of the user. Corresponding images are shown in Appendix 10.5 to illustrate the switching devices. The switching devices listed are similar to those used in high-voltage applications (see section 4.3.2).

- ***Circuit-breakers*** are not only capable of switching operating currents but also separating and, if necessary, closing electrical circuits that carry fault currents (e.g. in the event of a short circuit). *Area of application: Primary and secondary distribution*. In secondary distribution (e.g. in RMUs), fused load-breaks are sometimes used as alternatives to circuit-breakers. These fused load-breaks can perform similar functions, yet they cannot fully replace circuit-breakers, because their fuses are irreversibly tripped by high currents, whereas circuit-breakers can be switched back on.

- ***Load switches*** are used to switch electrical equipment and installation parts on and off under normal load conditions. Unlike circuit-breakers, they cannot interrupt short-circuit currents.

- ***Disconnecting switches*** disconnect downstream electrical equipment which is no longer energised from current-carrying parts. As such, they form a visible, reliable isolation gap, separating the downstream electrical equipment. This is mainly used to ensure safety during service and repair work. Disconnecting switches are actuated only in a current-free state. If a disconnection process were to be initiated under load conditions, a disconnecting switch would be destroyed (unlike a load switch or circuit-breaker).

- A ***load-break switch*** is a switch that doubles as a load switch and a disconnecting switch. Area of application: mainly secondary distribution, but also primary distribution.

- ***Fused load-breaks*** are used as alternatives to circuit-breakers in RMUs to protect transformers. During normal operation, only the load-break switch is used. In the event of a short circuit, the fuse burns out, triggering a switch-off. *Area of application: Secondary distribution,* e.g. in the transformer bay of an RMU.

- A ***grounding switch*** is a mechanical switching device for grounding the electrical equipment in an electrical circuit (e.g. for protection during maintenance work). Under normal operation, it conducts no current, but, when anomalies occur (e.g. a short circuit), it withstands electrical currents for a certain amount of time.

Table 3 shows the switching devices typically used in switchgear for primary and secondary distribution.

Table 3: Use of switching devices in medium-voltage switchgear
Source: Own research

Components	Primary	Secondary (RMU)
Circuit-breakers	always	either or (often fused load-breaks, rarely circuit-breakers)
Fused load-breaks	rarely	
Load-break switches	rarely	usually
Disconnecting switches	always	only in combination with circuit-breaker
Grounding switches	always	always

Additional switchgear components

Aside from the actual switching devices, switchgear also includes additional components. The composition depends on the specific application for which the switchgear is used. For the four components described below, only the insulation properties and heat dissipation of the insulation medium used are significant, since no switching processes occur here.

- ***Busbars*** are arrangements of conductors in the form of rails/bars, to which the circuits can be connected. Busbars can be insulated with gas (including air), solids or liquids.

- ***Instrument transformers*** transform current/voltage so that metering devices can be connected (Figure 12). Current transformers transform alternating currents, while voltage transformers transform alternating voltages. Instrument transformers are integrated directly into medium-voltage switchgear, always outside the gas compartment (primary and secondary distribution). In medium voltage applications, instrument transformers are insulated mainly using solids (cast resin, epoxy resin). For some years, the prioritisation of hardeners for the epoxy resins used here (MHHPA and HHPA anhydrides) has been a topic of discussion within the context of the REACH approval process. The evaluation may lead to a restriction or approval procedure for these substances, which will have consequences for manufacturers of instrument transformers [ZVEI, 2016]. The potting of insulation for instrument transformers usually takes place at low pressure to prevent air voids and/or partial discharges during operation (see section 4.2 on problems related to partial discharge).

Compared with current transformers, voltage transformers are wound with very thin wires on the high voltage side which exposes the insulation material around the wires to high electric field stresses. To prevent the formation of air inclusions in this critical area, voltage transformers are sometimes also potted inside an SF_6 atmosphere.

- ***Bushings*** are fixtures that lead a conductor through a wall (e.g. building wall, grounded enclosure of a transformer) while electrically isolating the conductor from the wall. Nearly 100% of bushings used in medium-voltage applications are bushings inside switchgear. Solid insulators like epoxy resin are generally used to insulate these bushings.

- ***Surge arresters*** are used to protect electrical equipment against excess voltages caused by lightning strikes or external switching processes. In medium-voltage applications, zinc oxide is most often used as the active part of surge arresters. Fibreglass-reinforced plastic and silicone are used for outer insulation.

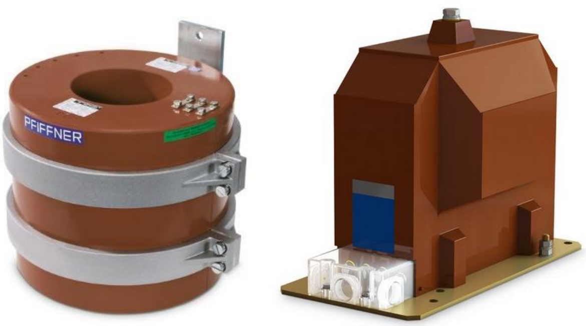

Figure 12: Medium-voltage current transformer (left) and voltage transformer (right)
Source: [Pfiffner Messtechnik]

Switching devices for generators

Generator circuit-breakers are switching devices that are installed between a generator and transformer for protection (Figure 13). The functions of the generator circuit-breaker are to connect the generator to the grid (or, in pump storage power plants, to provide a fast switch-over between generator and motor operation) and to interrupt operating currents and fault currents. Because of the very high currents near generators, the electrical requirements for generator circuit-breakers are much higher than those for circuit-breakers used in the grid. Generator circuit-breakers can be designed as gas circuit-breakers or with vacuum technology. However, for very high rated currents (generators above 450 MVA), only SF_6-generator circuit-breakers are available on the market and no vacuum circuit-breakers. Pressurised air technology has largely been superseded in generator circuit-breakers, first by SF_6 and later by vacuum.

Figure 13: Gas-insulated generator circuit-breaker (Alstom)
Source: Product sheets (see Appendix)

4.3.2 High-voltage electrical equipment

High-voltage switchgear (Figure 14 and Figure 15) includes all switchgear with a rated voltage of > 52kV. These are found on the high voltage side of transformer stations between medium voltage and high voltage as well as between extra-high and high voltage. They are also found in coupling, transfer and transformer stations (see section 4.4) in the high and extra-high voltage levels. For high-voltage switchgear, the two design types AIS and GIS differ more significantly in size than they do in medium-voltage (see Figure 14 and Figure 15).

With its compact size, a GIS can be installed in urban areas. Another possibility is the construction of a switchgear in the form of a so-called hybrid switchgear (Figure 14, right). This is a combination of GIS and AIS, in which the air-insulated busbars are connected with gas-insulated components. Hybrid switchgear is used mainly as a supplement to AIS, since hybrid installations are smaller and their installation is considerably simpler and faster than that of AIS. This is because the components (circuit-breakers, disconnecting switches, grounding switches and instrument transformers) are pre-assembled and tested in the factory. Air-insulated switchgear with a gas-insulated dead tank circuit-breaker (see below) is a form of a hybrid installation, though it is usually referred to as an AIS.

Figure 14: High-voltage transformer station for a hydroelectric power plant

Left: Before renovation: Air-insulated switchgear (AIS) Right: After renovation: Hybrid switchgear (ABB) Source:

Source: Product sheets (see Appendix)

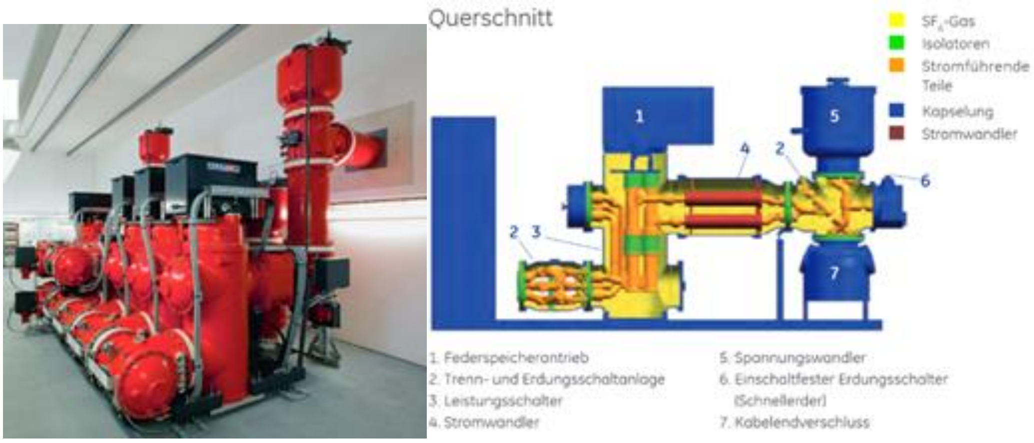

Figure 15: Left: 110kV gas-insulated switchgear (GIS) with ten bays Right: Cross-section of a 72.5kV gas-insulated switchgear (GIS) (GE)

Source: Product sheets (see Appendix)

Switchgear components

In general, the same components are used as in medium-voltage switchgear (section 4.3.1), except that load switches, load-break switches and fused load-breaks are generally not used in high-voltage applications. Because of the high voltage level, the specific design of the components differs, particularly in terms of the arc-quenching and insulation media used. For GIS, all components are gas-insulated (pressurised inside a closed gas compartment), while for AIS, some components are gas-insulated and others can be air-insulated (see Figure 8). The table below provides an overview of the possible gas-insulated components depending on the design of the switchgear.

Table 4: Components in gas-insulated switchgear (GIS) and air-insulated switchgear (AIS), which can contain SF_6 as the insulating or arc-quenching gas. SF_6 alternatives are listed in chapter 6
Source: Own research

Components	Switchgear type	
	GIS	AIS
	Component is gas-insulated	
Circuit-breaker and bushing	X	X
Disconnecting switch, grounding switch	X	
Instrument transformers	X	X
Surge arrester	X	

Circuit-breakers take over the function of quickly breaking an operating current as well as the fault currents relevant for design (e.g. in case of short circuit). Compared with medium-voltage applications, the isolation gap for circuit-breakers in the high-voltage must, after interrupting the electrical current, safely withstand higher voltages, which generally makes vacuum designs more difficult. Currently, SF_6 designs are the most commonly used. Vacuum designs already exists in the HV and are in development for the use in the extra high-voltage [Smeets et al., 2014]. Two different designs are used in air-insulated high-voltage installations (Figure 16):

- *Live tank circuit-breakers*: circuit-breakers in which the interrupter is inside an enclosure that is insulated from ground potential.

- *Dead tank circuit-breaker*s: circuit-breakers in which the interrupter is situated inside a grounded metallic enclosure. Therefore, a current transformer can be installed directly at the bushing, whereas with live tank circuit-breakers, a current transformer (see Figure 16) must be installed separately. As a result, dead tank circuit-breakers take up less space. However, to insulate the current-carrying components of the metallic enclosure, dead tank circuit-breakers require substantially higher volumes of insulation gas. Furthermore, bushings are necessary at the enclosure for the high-voltage connection, and these are often also filled with SF_6.

Figure 16: Left: High-voltage SF_6 live tank circuit-breaker (72.5-170kV, ABB), right: high-voltage dead tank SF_6 circuit-breaker (145kV, Siemens)
Source: Product sheets (see Appendix)

Instrument transformers are used for metering current (current transformers), voltage (voltage transformers) and current and voltage (combination transformers). AIS for the lower voltage levels of HV mainly uses oil paper as its arc-quenching medium, though SF_6 is increasingly used at higher voltages (Figure 17). For instrument transformers, only the insulating properties and heat dissipation (not the arc-quenching properties) of the insulation medium are relevant.

Figure 17: High-voltage instrument transformers
Left: High-voltage current transformers at a transformer station. Right: High-voltage voltage transformer (outlined in red) in a gas-insulated switchgear (Pfiffner Messwandler AG)
Source: Product sheets (see Appendix)

Bushings sometimes also use a gas-insulated design in high-voltage installations, especially starting at a certain size. There are two different types of bushings used in encapsulated electrical equipment/switchgear. In the first type, the bushing is connected to the gas compartment of the electrical equipment/switchgear (see Figure 18). In the second type, the open-air side of the bushing is closed off from the electrical equipment/switchgear by a gas-tight, solid insulator.

There are variations on this design in which the space between the solid material and outer insulator is filled with foam. SF_6 can be used as a propellant in this process. As with instrument transformers, only the insulation properties and heat dissipation (not the arc-quenching properties) of the insulating medium are relevant to bushings (Figure 17).

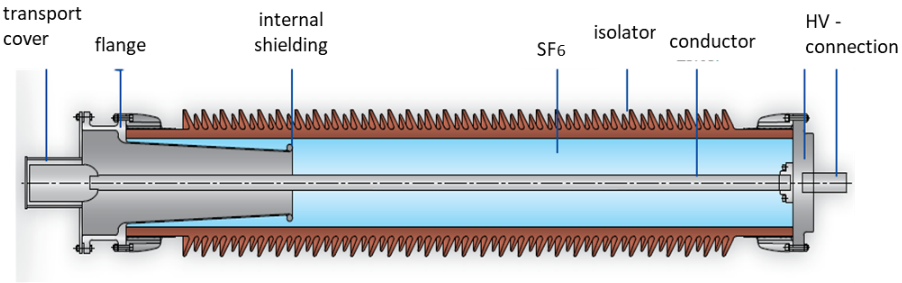

Figure 18: Cross-section of a bushing filled with SF_6 (GE)
Source: Product sheets (see Appendix)

4.3.3 'Other electrical equipment'

In current discussions, the electrical equipment group summarised in SF_6 reporting as 'other electrical equipment' has become increasingly relevant. This is due to the comparatively high level of production emissions generated by this electrical equipment group (see section 5.3**Error! Reference source not found.**). However, the debate is also c ontentious, because the system boundaries and terminology of this equipment group have not been conclusively defined, and different interpretations and/or standard terminologies exist. The allocation of stored ('banked') emissions is also controversial.

The National Inventory Report (NIR) [UBA, 2017] lists the following resources as 'other electrical equipment':

- Instrument transformers:
  - HV outdoor instrument transformers (all emission categories)
  - MV cast resin instrument transformers (only production emissions)
- Bushings:
  - HV bushings (only production emissions)
- Gas-insulated lines (GIL): (all emissions categories)
- Gas-insulated transformers: A marginal number exist within the grid; (no production emissions)
- Capacitors > 1,000V (only production emissions)
- Testing of MV components (only production emissions)

The function and relevance of instrument transformers and bushings have already been introduced in sections 4.3.1 and 4.3.2 as components of electrical equipment. Additional types or electrical equipment (gas-insulated lines (GIL), gas-insulated transformers (GIT) and capacitors) are briefly explained in the following paragraphs.

Gas-insulated lines (GIL)

A gas-insulated line (GIL, Figure 19) is an electrical extra high-voltage line consisting of a conductor pipe that is centred inside a pipe which contains a compressed insulation gas (usually SF_6 or SF_6/nitrogen mixtures with an SF_6 concentration of approx. 20%). GIL (according to IEC) specifically refers to a gas-insulated pipeline for transmitting energy across greater distances (> 500m) used instead of a cable or overhead line.

In everyday language, gas-insulated busbars in transformer stations are often also referred to as GIL. These are used for connecting the transformer directly with a GIS. The combined lengths of all gas-insulated busbars in a transformer station can add up to several kilometres. A gas-insulated busbar contains screwed and sealed flanges. Meanwhile, a GIL consists of gas-tight, welded tubes, with the advantage of lower leakage and therefore lower emission rates.

Compared to cables or overhead lines, GILs offer certain advantages. GILs can be laid either in concrete pipes/blocks or underground and require less space than overhead lines, making them useful in urban areas or in the direct vicinity of airports. GILs allow transmission powers and high operating voltages of 400 and 500kV typically and require low power factor correction compared with extra-high voltage cables. GILs cost many times more than equivalent overhead lines. Because of the acceptance problems facing additional overhead lines, GILs are becoming increasingly important as an alternative to overhead transmission lines in cases where overhead lines cannot be installed. Currently, GILs are also being developed for high-voltage, direct-current transmission [Tenzer et al., 2015].

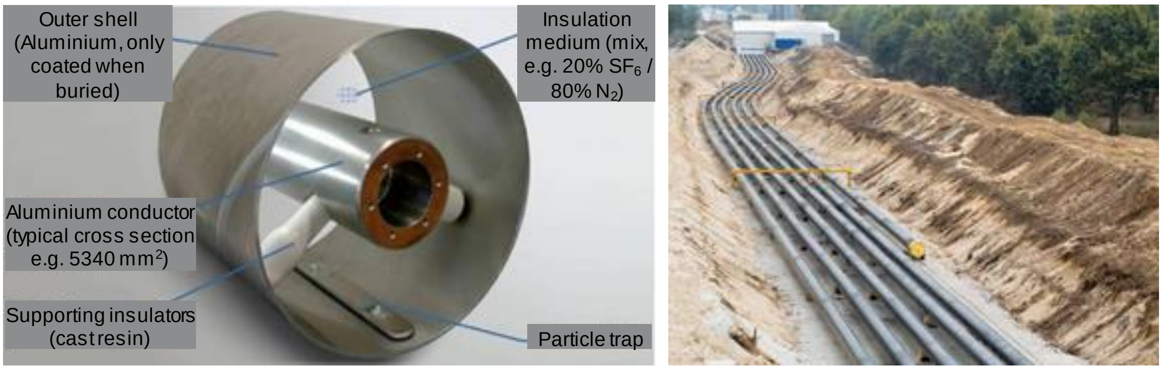

Figure 19: Gas-insulated lines

Left: Structure of a gas-insulated line (GIL). Right: Laying a gas-insulated line (GIL) underground

Source: Product sheets (see Appendix)

Gas-insulated transformers

A transformer transfers (converts) electrical power from one voltage level to another voltage level, while the transmitted power (the product of current and voltage) remains the same except for losses. Transformers are used between all voltage levels (from low to extra-high voltage). In Europe, most transformers are oil-insulated, although solid-insulated transformers are also used in lower voltage ranges and special applications. Gas-insulated transformers are practically never used. In contrast to oil-insulated transformers, gas-insulated transformers reduce the risk of fire and do not require oil catchment containers. Gas-insulated transformers are widely used in some parts of Asia and occasional installations can be found in the USA.

Capacitors

SF_6-filled capacitors (often in combination with oil) are used in power electronics in the lower MV (up to approx. 5kV). Since they are used primarily in railway applications, they are not considered components of the distribution and transmission grid as such. Among these capacitors, SF_6 emissions generally only occur during the production stage [Wartmann und Harnisch, 2005].

4.4 Application-specific requirements for switchgear

Below is a summary of the aforementioned applications for the types of switchgear listed and their components. The summary provides details about application-specific requirements.

Generally, switchgear is installed at different places in the grid. We divide the use of switchgear into three types of applications:

- *Generation:* Switchgear for connecting and use within non-public networks of power plants;
- *Public grids:* Switchgear at power grid nodes for distribution within one grid level or transforming between two grid/voltage levels;
- *Customer plants:* Switchgear for connecting and use within non-public grids belonging to electricity consumers.

Most switchgear is installed in the public grid, where it is found at grid nodes for distribution within one grid level or transforming between two grid/voltage levels. The functions of the switchgear vary depending on the voltage level as well as the type and location of the connected generators and consumers. Figure 20 and Table 5 illustrate the general areas of application within the power system.

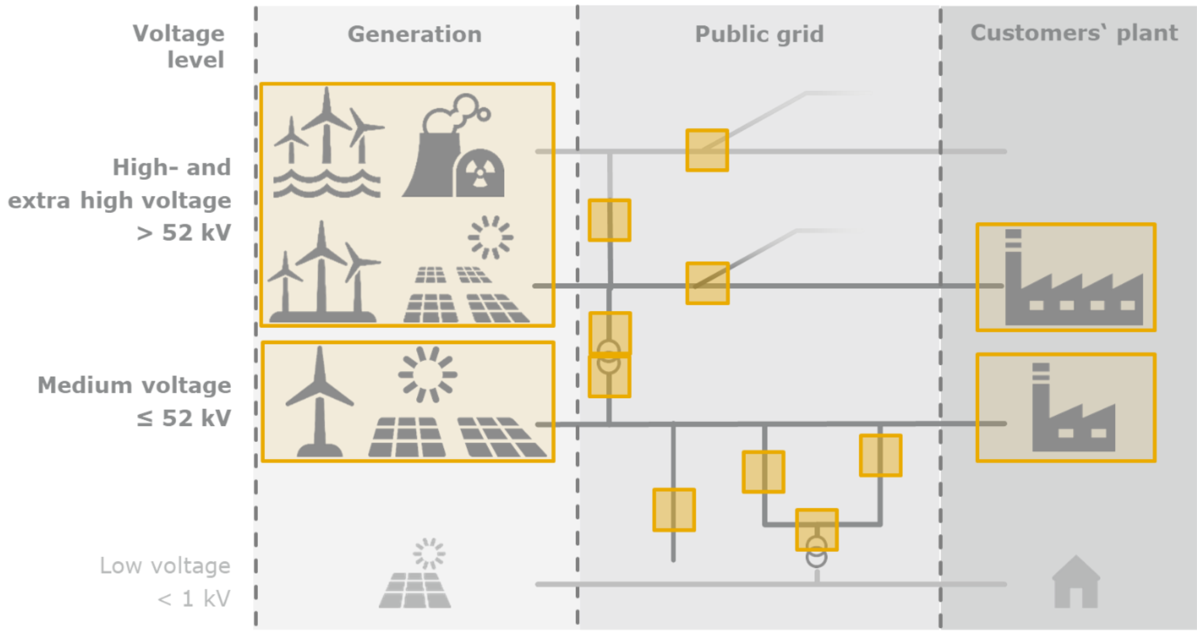

Figure 20: Overview of application sites for switchgear in which SF_6 is potentially used

Source: Own research.

Table 5: Areas of application for high- and medium-voltage switchgear

Source: Own research.

Voltage level	Electrical equipment	Area of application		
		Generation	Public grid	Customer plants
High- and extra-high voltage	**Switchgear**	Transmission station, offshore, wind, customer plants are integrated into (private) industrial networks.	Transformer stations	Large-scale industrial consumers
Medium voltage	**Switchgear (primary distribution)**	Transmission station, wind- and solar park	Transformer stations	Industrial networks, infrastructure projects
	Switchgear (secondary distribution)	Tower base, within a solar park	Local grid stations	Industrial networks, infrastructure projects
	Generator switchgear	Power plant connection	-	-

Based on this list, we assign six basic usage scenarios to the various areas of application and voltage levels. This does not reflect all possible, existing usage scenarios, but does enable the most important ones to be prioritised:

1. ***Local grid stations*** (switchgear for secondary distribution);
2. ***Switchgear in the tower bases of wind-power plants, onshore and offshore***, as well as for connecting **solar parks** (switchgear for secondary distribution);
3. ***HV-MV transformer stations or MV connection of power plants*** (switchgear for primary distribution);
4. ***Connection of industrial and commercial consumers as well as infrastructure projects (e.g. railway network);***
5. ***Connection of generators in power plants*** (generator circuit-breakers);
6. ***Transformer stations and switchgear in the high and extra-high voltage.***

See the sections above for a detailed description of the basic requirements for switchgear in transformer stations (primary usage scenarios 3 and 6). Beyond this, there are specific requirements for switchgear in some other usage scenarios. These are described in the following sections.

- ***Usage scenario 1: Local grid stations (switchgear for secondary distribution)*** Local grid stations distribute electrical energy at medium-voltage level or convert voltage from medium to low. Generally, local grid stations consist of components of MV primary technology (transformer and switchgear), additional MV secondary technology (measurement and control technology) and a low-voltage part. Circuit-breakers are generally not installed, since short-circuit currents can be switched in installations in primary distribution. Overloads and short circuits are usually controlled in the grid and at outgoing transformer feeders by a fused load-break (most common in Germany) or a circuit-breaker (only occasionally). The most frequent design is the RMU. Because of the high number of local grid stations required and their use in residential areas, grid operators, particularly in urban areas, set high requirements for compact size, as well as low maintenance and costs.
- ***Usage scenario 2: Switchgear in tower-bases of wind-power plants, onshore and offshore*** In the past, machine transformers and switchgear for wind-power installations were built on shore, near the tower base. Today, these components are found almost exclusively inside the tower base itself. Due to the limited space, also in complying with standards for the dimensions of escape and rescue paths, installation inside tower bases requires very compact designs. Gas-insulated switchgear for secondary distribution (stubs with two functional units as well as ring cables with three functional units) are used. Some tower configurations (concrete hybrid towers) being built today and in the future are wider in size than those built a few years ago. This makes size limitations less of an issue for these tower-bases. Tubular steel towers are transported across bridges, which means their sizes are limited. Even the size of the door for accessing the tower-base is a relevant design criterion, since large doors weaken the stability of the tower. Manufacturers of wind-power plants generally purchase and install switchgear that is serially produced for general applications. There are practically no custom-built products. Therefore, products are selected that fulfil the maximum requirements. Inside the tower base, it is generally possible to divide the plant parts onto two floors. However, this inevitably leads to additional costs. Switchgear installed in offshore wind power plants as well as in onshore installations near the coast must be protected against environmental influences due to their corrosive and conductive surroundings. Operation must be reliably maintained, even in the event of heavy fluctuations in temperature. Furthermore, low maintenance is a decisive criterion for use in offshore wind power plants, since there are only very few trained maintenance persons, and accessibility of the plant is a critical factor.

- ***Usage scenario 3: HV-MV transformer stations or MV connections of power generation plants (switchgear for primary distribution):*** Basic requirements for switchgear in HV-MV transformer stations and MV connections of power generation plants are described in detail in section 4.3.1.
- ***Usage scenario 4: Connection of industrial and commercial consumers:*** This switchgear is located near industrial processes associated with harsher environmental conditions (pollution levels, temperatures), a higher number of switching actions and elevated safety requirements with respect to power failures. As a result, there are higher requirements for lifetime and durability not only but especially for circuit-breakers and for the availability and operational safety of the installation. The switchgear found in industrial grids is mostly for primary distribution, though a large amount of switchgear for secondary distribution can also be found with specific requirements for rated voltage and current usage.
- ***Usage scenario 5: Generator circuit-breakers*** Generator circuit-breakers are installed for the generators of power plants. These are operated in medium-voltage, although they are characterised by very high operating currents, high short-circuit currents and a predominantly high DC portion. The requirement of conducting and switching very high rated operating currents of over 40kA poses a particular challenge for the switchgear.
- ***Usage scenario 6: Transformer stations and switchgear for high and extra-high voltage*** The basic requirements for switchgear in transformer stations and switchgear for high and extra-high voltage are described in detail in section 4.3.2.

5 Estimated number of installations, trends and developments

The section below classifies the use and emissions of SF_6 in the electrical power supply in Germany in the context of the worldwide climate relevance of SF_6. It also provides a regional comparison of how much SF_6 is used and emitted in the various usage scenarios.

5.1 Estimate of the amount of equipment in medium- and high-voltage

Switchgear in Germany is classified into installations for the public network, installations for connecting generation plants, and installations in customer plants (primarily in heavy industry and infrastructure). There is currently no exhaustive installation registry for switchgear and other components containing SF_6 in Germany.[7] While estimates exist for the amount of grid electrical equipment in use, such as the number of transformer stations, the number of switchgear installations and functional units (for example, per transformer station) varies heavily. Therefore, for a rough, tentative estimate, we refer to the number of transformer stations, local grid stations and production plants found in FNN outage statistics and reporting by producers. Generally, estimates are more accurate for the higher voltage levels (high and extra-high voltage). The distribution of existing equipment for generation, transport and heavy industry was estimated based on interviews with experts. A reliable quantitative estimate of the amount of 'other electrical equipment' in use, such as instrument transformers or bushings, is impossible with the information currently available.

Estimated number of switchgear[8]

Table 6 shows the estimated distribution of installations in Germany across the different voltage levels, as well as a categorisation of the switchgear according to application type. The distribution figures are based on reporting by producers and market research. They represent averaged mean values. We have validated the numbers and the assumptions made in the course of interviews and discussions with users and manufacturers. However, these should be interpreted only as tentative estimates.

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[7] The current calculation of the amount of SF_6 in Germany is made using a running inventory based on reporting from manufacturers. Emissions are determined based on an emissions factoring method. Since the accruing gas quantities for each equipment heavily depend on the technology, the manufacturer or the year of commissioning, a valid estimation of the plant population is impossible based on the aggregated quantities specified.

[8] Depending on the number of branches, a switchgear consists of one (single station) or more functional units. Since the amount of SF_6 used increases proportionally to the number of functional units, we have selected the functional unit as the basic unit for the system population.

Table 6: Estimated distribution of existing MV and HV switchgear and functional units in Germany by application type (numbers as of late 2015)
Source: Own research based on interviews with experts and [ABB et al., 2003; E-Bridge et al., 2014; MarketsandMarkets, 2016; Neumann et al., 2004]

Voltage level	Electrical equipment	Estimated percentage of functional units in the area		
		Generation	Public grid	Consumption/ industrial grids and infrastructure
Medium voltage	Switchgear (primary distribution)	10%	45%	45%
	Switchgear (secondary distribution)	5%	65%	30%
	Generator circuit-breakers	100%	-	-
High voltage	Switchgear	1-2%	>90%	5%

In Germany, there are currently about 5,000 switchgear installations and 25,000 functional units in high-voltage (110kV level) and about 500 switchgear installations and 3,000 functional units in extra-high voltage (>110kV level) of the public grid [E-Bridge et al., 2014; FNN, 2014]. Only a few consumers have their own HV switchgear. They represent about 5% of the total number of HV switchgear installations. Onshore and offshore wind farm operators are connected to the 110kV grid via transformer stations including switchgear (110kV/20kV). These are partly operated by the wind farm operators themselves. However, the share of producers in the total stock is low and is currently around 1-2%.

A HV transformer station outputs medium-voltage rings via busbars. Each of these MV outputs normally has one MV functional unit for primary distribution. In total, we estimate the number of installations for primary distribution in the public network at 7,500 switchgear installations and about 100,000 functional units. In addition, there are just under 9,000 switchgear installations for connecting wind and solar parks [E-Bridge et al., 2014]. In industrial networks, the number of the installed switchgear for primary distribution is on the same scale as in public networks, according to reporting by producers, although the number of functional units is lower. We estimate the total number of functional units for primary distribution to be more than 500,000 units.

MV networks are designed as ring networks in most cases. On average, such a medium-voltage ring contains 14 local grid transformers. This number fluctuates significantly between urban and rural regions. In total, about 500,000 switchgear installations for secondary distribution are installed in Germany in public networks.

A majority of these switchgear installations (more than 90%) are RMUs consisting of three functional units. In public German networks, a total of 1,000,000 functional units are installed. The main consumers of switchgear for secondary distribution are grid operators [E-Bridge et al., 2014]. According to manufacturers' estimates, heavy industry and large commercial enterprises also represent a significant consumer market for switchgear for secondary distribution. In the area of generation, switchgear for secondary distribution are installed in or near tower bases of wind-power plants (onshore: about 30,000 units; offshore: 1,000 units) or for connecting solar parks (around 40,000 units) [BWE, 2015].

The total number of generator circuit-breakers is estimated at around 2,000 units.

In total, we estimate the scale of the existing population of functional units as follows:

- more than **500,000 functional units (ballpark figure) for primary distribution** in MV.
- more than **2 million functional units (ballpark figure) for secondary distribution** in MV.
- more than **25,000 functional units in high-voltage range and more than 3,000 functional units in extra-high voltage.**

Estimated population of switching devices

The existing number of switching devices (circuit-breakers and load-break switches) can be estimated based on the number of functional units and switchgear installations. It should be noted that switching devices are each three-phase current sets (one design for each phase).

In high and extra-high voltage, generally one functional unit is used with one circuit-breaker set for each outlet. As a result, about 25,000 circuit-breaker sets are installed in high-voltage. In extra-high voltage, there are about 3,000. Also for primary distribution in medium-voltage, there is one circuit-breaker set for each functional unit. However, in secondary distribution in Germany, a circuit-breaker is only used in response to specific customer requests. The percentage of functional units with circuit-breakers in secondary distribution is about 5%. As a result, there are about 300,000 three-phase current sets of circuit-breakers in Germany in primary and secondary distribution. Load-break switches are the main components in secondary distribution. In the most common configuration as RMUs, one load-break switch is used for each ring cable inlet and outlet. For the functional unit of the transformer output, a fused load-break switch is used in most cases. However, in rare cases, the transformer output can itself be designed as a circuit-breaker. Assuming that about 90% of the functional units in secondary distribution switchgear are designed as load-break units, the number of load-break switches can be estimated at about 2 million units.

Estimate of the population of 'other electrical equipment'

Along with switchgear in medium- and high-voltage networks, gas-insulated lines occupy a relevant position in the stock of electrical equipment. These are installed only in the extra-high voltage. According to a study by the VDE [Schöffner et al., 2006; Baer et al., 2002], 50km of gas-insulated lines were installed in Germany between 1975 and 2002.

However, the study does not differentiate between gas-insulated power plant output lines and gas-insulated lines in the public network. Since then, very few significant, large-scale projects have been executed. Examples are the 5,400m[9] GIL at Frankfurt Airport and 2,610m GIL installed by the Munich public utilities:

No reliable quantitative estimate of the quantity of 'other electrical equipment' in use, such as instrument transformers or bushings, can be made on the basis of the information currently available.

Trends and development of the electrical equipment stock

The inventory of electrical equipment described above reflects the current situation. Furthermore, interviews with experts revealed trends that will influence the development of existing installations in future.

In general, grid expansions will primarily affect medium-voltage installations [Büchner et al., 2014; Agricola et al., 2012]. Drivers identified for this development include:

- Smart grids and ICT-penetration of the distribution network,
- Electromobility,
- Shore-side power supply of ships,
- Increases in wind energy (on/offshore).

According to experts, the use of intelligent systems like smart meters is not expected to lead to any expansion in terms of switchgear installations. However, it will be necessary to modify switchgear into automated, controllable units.

With the rise of electromobility, it will also be necessary to reinforce the power grid. Likewise, the trend of shore-side power supply for ships requires a strengthening of the grid as well as switchgear with higher rated voltages and currents.

The expansion of wind energy in Germany through onshore and offshore wind-energy installations will lead to a further increase in the use of switchgear. However, manufacturers do not expect drastic increases in proportion to the total number of existing switchgear installations. Currently, switchgear for secondary distribution used in tower bases are insulated almost exclusively with SF_6 due to the emphasis on compact size. However, maintenance-free alternatives in the area of offshore wind energy present a major advantage. Maintenance at sea poses a major challenge, since deploying maintenance staff and vessels sometimes involves lengthy waiting times. If leakages occur in switchgear at sea, SF_6 may continue to leak undeterred for a long time. This would not be a problem if more environment-friendly gases were used. A risk exists only if the dielectric strength drops too low as a result of severe leakage.

The expansion of wind energy plants on land and at sea also has consequences for HV grid expansion. The connection to the public grid requires some additional switchgear. However, the effects are lower here.

[9] two parallel systems, each with three phases over 900m.

5.2 Estimate of the proportionate use of SF_6 as insulation and arc-quenching medium in existing installations

Not all switchgear installations and their components in the existing electrical equipment use SF_6 as their insulation and arc-quenching medium. The information in Table 7 regarding GIS as a percentage of total equipment in each area of application is based on grid data from FNN outage statistics [FNN, 2014]. It should be noted that the FNN outage statistics only list equipment used in public grids. Current market developments towards GIS also cannot be estimated.

Table 7: GIS (using SF_6 as insulation medium) as a percentage of German electrical equipment installations
Source: Own research based on [FNN, 2014]

Voltage level	Switchgear	GIS (using SF_6 as insulation medium) as percentage of total electrical equipment installed in 2013
Medium voltage	Functional units for primary distribution	20%
	Functional units for secondary distribution	35%
	Generator circuit-breaker installations	60%
High voltage	Functional units	15%
Extra-high voltage	Functional units	6%

For medium-voltage switchgear for secondary distribution, the percentage of GIS using SF_6 as insulation medium is especially high due to the advantages described in previous chapters (e.g. low space requirements, low maintenance due to sealed pressure systems, protection against external influences, cost). The share is also assumed to be on the rise.

On the primary distribution level, custom installation is more often necessary with regard to rated current and the number of functional units. Furthermore, space requirements at transformer stations in rural areas are not a critical factor. Also or historical reasons, medium-voltage switchgear for primary distribution are more often air-insulated.

The percentage of generator circuit-breaker installations using SF_6 as their insulation medium depends on the maximum operating and fault currents. Vacuum technology is state-of-the-art for currents up to 50kA. Among switchgear capable of switching fault currents up to 80kA, the ratio between SF_6 and vacuum technology is approximately equal. Above 80kA, SF_6 is used almost exclusively. Thus far, only one manufacturer supplies vacuum switching tubes for generator circuit-breakers capable of breaking currents of up to 100kA.

High- and extra-high voltage switchgear consists primarily of open-air installations. Gas-insulated switchgear has become prevalent only in urban areas or areas with limited space.

Circuit-breakers in medium-voltage are designed as vacuum switching tubes as well as with SF_6 as their arc-quenching medium, although the trend favours vacuum technology. Oil and minimum-oil circuit-breakers have been replaced almost entirely in the medium-voltage [Leonhardt et al., 2000]. Load-break switches in gas-insulated, MV switchgear are designed almost exclusively with SF_6 as their arc-quenching medium and are installed inside the hermetically sealed gas compartment. As a result, in the medium-voltage in Germany, the percentage of SF_6 load-break switches is equal to that of gas-insulated switchgear.

In the high-voltage too, switching devices for gas-insulated switchgear are designed as SF_6 switches. In open-air installations, the majority of live tank circuit-breakers use SF_6 (see section 4.3.2). For historical reasons, however, oil circuit-breakers continue to be installed for high-voltage installations [Balzer et al., 2004]. Vacuum circuit-breakers have been available in Europe since 2010[10] in the high-voltage. In total, we assume that 75% of circuit-breakers in open-air installations are SF_6 live tank products. The remaining 25% are oil circuit-breakers. This means that SF_6 is used as the arc-quenching medium for 85% of installations in the total inventory of high-voltage circuit-breakers in AIS and GIS.

Instrument transformers in GIS are also SF_6-insulated. In open-air systems in Germany, oil paper is most often used as the insulation medium. Only in rare instances, SF_6 is used in instrument transformers for the 110kV grid. The proportion of SF_6-insulated instrument transformers increases at higher voltage levels.

Table 8 gives an overview of the percentages of switching devices using SF_6 as their arc-quenching medium.

Table 8: Percentage of components using SF_6 as arc-quenching and insulation medium. Existing installations in Germany Source: Own research based on interviews with experts and [Balzer et al., 2004; MarketsandMarkets, 2016]

Voltage level	Switchgear components	Percentage of components with SF_6 design
Medium voltage	Circuit-breakers	30%
High voltage	Circuit-breakers	85%
	Disconnecting switches	30%
	Instrument transformers	35%

[10] Vacuum circuit-breakers became available in Japan much earlier than this.

5.3 Estimate of installed SF_6 volumes and emissions

Estimate of installed SF_6 volumes in Germany

Using previously recorded installation figures and the SF_6 volumes for each type of electrical equipment, it is possible to derive reference values for the total volume of SF_6 installed in Germany. The total volume of SF_6 installed in switchgear in Germany is calculated in manufacturer and operator monitoring using a model-based approach. The results of this survey are shown in Table 10.

Weighted SF_6 volumes per electrical equipment installation

Table 9 shows reference values for SF_6 volumes used in electrical equipment. This shows that low SF_6 volumes are used per electrical equipment installation in the medium-voltage. Due to the high total number of switchgear installations using SF_6 as their insulation medium, a very high volume of SF_6 is installed in medium-voltage installations in Germany. The volume of SF_6 used depends on the enclosure design, the insulation of busbars (SF_6 or solids) and rated voltage and current. The value specified for medium-voltage switchgear (primary and secondary distribution) refers to one functional unit. Since three functional units are used in RMUs, the SF_6 volume must be tripled for the complete switchgear. Switching devices in the medium-voltage are usually installed directly inside the SF_6 compartment and are therefore not listed separately in the table. There are a few circuit-breakers that use SF_6 as their arc-quenching medium but a solid or air as their insulation medium. In these exceptions, about 0.3kg of SF_6 is used for each circuit-breaker.

The specific SF_6 volumes used in HV electrical equipment are many times higher than the volumes used in similar electrical equipment in the MV. Due to the lower number of installations, the total volume of SF_6 used in the high-voltage is, however, somewhat lower than the total volume use in the medium-voltage. In gas-insulated, HV switchgear, between 90 and 170kg of SF_6 are used for each functional unit, depending upon the configuration. The volume of SF_6 used in HV circuit-breakers in open-air installations depends on the technology used. Due to their additional grounding, dead tank circuit-breakers require many times more SF_6 than live tank circuit-breakers. However, Germany almost exclusively uses live tank circuit-breakers, each of which uses about 7 to 9kg of SF_6.

The design prevalently used today for GIL in extra-high voltage uses 20% SF_6 and 80% N_2 as an insulation gas mixture, with between 1.3 and 1.8kg of SF_6 for each meter and phase. If pure SF_6 is used as the insulation medium, up to 10kg of SF_6 are installed for each meter and phase.

Table 9: Average SF_6 volumes per installation at each voltage level

Source: Own research based on product sheets, interviews with experts and [Koch, 2003; FNN, 2016; Widger, 2014]

Electrical equipment and components	Switchgear and components	SF_6 volume in kg per installation (average)
Medium-voltage electrical equipment	Switchgear for primary distribution (per functional unit)	2.5–3.5kg
	Switchgear for secondary distribution (per functional unit)	0.7–2.5kg[11]
	Generator circuit-breaker installations (per functional unit)	4–6kg
High- and extra-high voltage electrical equipment	High-voltage switchgear (per functional unit)	90–170kg
	Extra-high voltage switchgear (per functional unit)	~ 380kg
High-voltage switchgear components	Circuit-breakers (per phase)	Dead-tank: 25–40kg Live-tank: 7–9kg
	Instrument transformers (per phase)	(72.5kV) 5kg (245kV–550kV): 35-50kg

SF_6 volumes in existing electrical equipment

The model-based values collected by the ZVEI and FNN within the scope of the industry's voluntary self-commitment reveal a similar picture in terms of total SF_6 volumes in existing equipment. The highest total SF_6 volumes are found in the medium-voltage, even though specific SF_6 quantities for each MV installation are low. Table 10 shows the SF_6 volumes reported by the trade associations ZVEI and FNN during an inventory performed in 2016.

[11] This information applies per functional unit. There are three functional units in RMUs. Therefore 3 x 0.7kg of SF6 are used on an average in an RMU.

Table 10: SF_6 volumes in existing installations as reported by ZVEI and FNN
Source: Own research based on [Koch, 2003; FNN, 2016; Widger, 2014]

Electrical equipment and components	Estimate of SF_6 volumes in existing installations (ZVEI/FNN/VIK)
Medium-voltage electrical equipment	1–150t
Gas-insulated high-voltage switchgear (> 52kV) (including circuit-breakers and instrument transformers contained in installations)	840t
High-voltage switchgear (> 52kV)	300t
Instrument transformers for high voltage (> 52kV)	240t

We intentionally avoid comparing estimated SF_6 volumes with the estimated installation population because both estimates are aimed only at gaining an initial scope of the magnitudes and should be interpreted with great caution. For a valid calculation of the volumes, a suitable installation registry would be necessary.

Estimating emissions in Germany

To assess the overall climate relevance of electrical equipment, it is not enough to simply look at the volumes of SF_6 installed. What matters is the amount of SF_6 that is released into the atmosphere during the entire life cycle of a product (from production to normal operation to disposal). Figure 21 gives an overview of emissions released during production and normal operation in 2015 [SOLVAY et al., 2005; UBA, 2016]. Emissions of about 0.2 t released during disposal of products in 2015 are negligible. The emissions shown in Figure 21 and Figure 22 as well as in the following paragraphs result from an analysis of the values reported to the German Federal Environmental Agency by ZVEI and FNN.

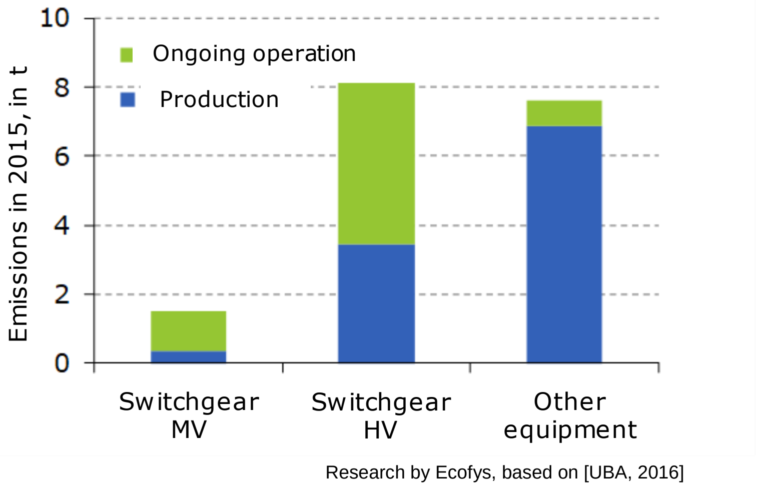

Figure 21: SF_6 emissions from production and operation; emissions from disposal are negligible (2015).
Source: Own research based on [SOLVAY et al., 2005; UBA, 2016]

The figure clearly shows that the highest sources of current emissions are operation of high-voltage installations (> 52kV) as well as production of electrical equipment. Emissions released during decommissioning and disposal are thus far very low in all applications, despite the high emission factor. This is because most gas-insulated switchgear have yet to reach the end of their life cycles. In the future, an increase in emissions in this category is to be expected, despite the fact that losses will be lower per unit[12].

The high emissions reported in the production of 'other electrical equipment' are probably the result of using SF_6 during production of instrument transformers, bushings and capacitors. In some cases, the SF_6 stored in the equipment, which can sometimes be emitted over the product's lifetime or cannot be recovered at the end of the product's life cycle, is completely attributed to the production emissions. The export of electrical equipment to other countries can result in skewed statistical information. An accurate analysis and validation of the reported numbers is currently being done by the trade associations and the SF_6 Work Group.

Current emissions from high-voltage installations are many times higher than those from medium-voltage installations, even though more SF_6 is installed in medium-voltage applications. The emission factor is higher, because high pressures are used in the high-voltage (6 bar instead of 1.3 bar in the medium-voltage), the overall dimensions are larger and HV-GIS are usually closed pressure systems whereas MV-GIS are usually sealed pressure systems (see sections 4.2). Generally, no gas is refilled in medium-voltage systems during the operating period [SOLVAY et al., 2005].

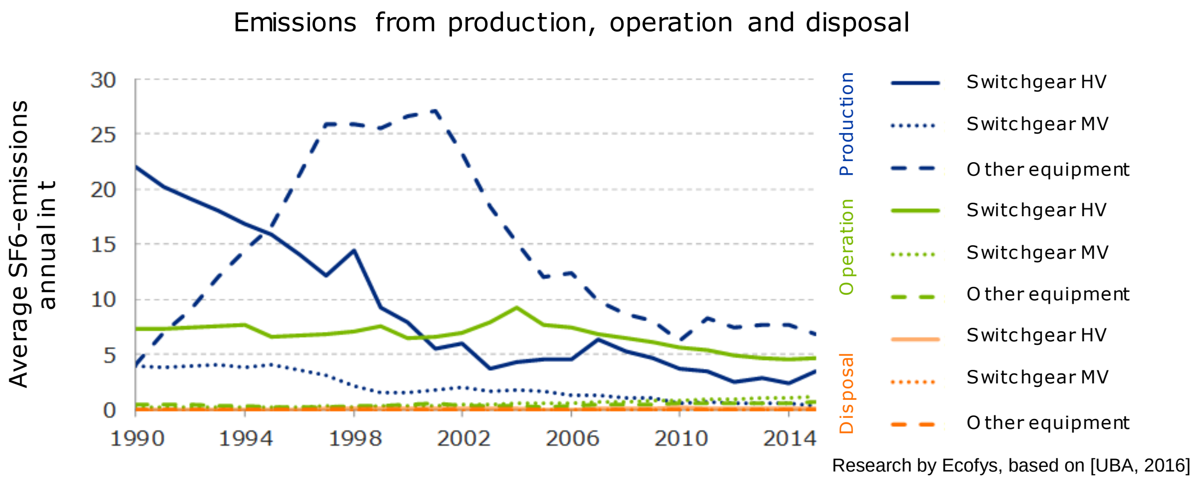

Figure 22: SF_6 emissions (in tons) from production, operation and disposal of MV and HV switchgear and 'other electrical equipment'

Source: Own research based on [SOLVAY et al., 2005; UBA, 2016]

In recent years, manufacturers have been able to greatly reduce overall emissions in the power supply thanks to technological advances in the manufacturing process and plant design. Figure 22 shows that the reduction of

[12] According to EU regulations, the extraction of SF_6 at the end of a product's life cycle must be performed by specially trained personnel. SF_6 is recovered and possibly reused after drying and purification. Losses that occur while handling the gas are expected to be low.

emissions can be attributed in particular to improvements in production processes. Improvements in existing high-voltage systems have also led to reductions. Current emissions from MV switchgear and 'other electrical equipment' are increasing at a low level.

5.4 Classification of existing installations and emissions in the international context

The previous sections discussed existing equipment, the use of SF_6 and emissions in the electrical power supply in Germany. Compared with other countries in Europe and around the world, there are notable differences, some examples of which are listed here.

Existing equipment and insulation media

In the medium-voltage, 12kV and 24kV installations (rated voltage) are used in Germany almost exclusively. In Austria, Spain and Great Britain, a high number of 36kV switchgear installations (rated voltage) are used in public primary and secondary distribution. Driven by the increasing plant capacity among newer generation wind power plants and wind parks, Germany is also increasingly shifting from 24kV to 36kV switchgear. While solid-material insulation is used less frequently in medium-voltage switchgear in Germany, its percentage is higher in the Benelux, Scandinavia, Poland and other Eastern European countries.

In high-voltage production in Germany, oil paper is used almost exclusively as the insulation medium for instrument transformers in open-air installations. In Eastern Europe, SF_6 is very often used in this application.

Emission rates among existing installations

In the literature, emission rates of existing installations are often used as metrics for international comparisons. These are usually indicated in terms of the percentage of SF_6 volumes present in the installed switchgear per year. At the same time, it is unclear whether the same reference basis is used in the different studies. Nevertheless, these percentages can be seen as reference values. In this regard, Japan and Switzerland are considered the global benchmarks for low emission values with 0.07% in Switzerland [SwissMem, 2017a] and 0.14% in Japan [Saida, 2014] for the entire power supply (average throughout HV and MV). The European average is estimated by the manufacturers at 2.5% for HV and 0.7% for MV. The IPCC calculated values of 2.6% for high voltage and 0.2% for medium voltage in 2006 [IPCC, 2006].

Emissions during the entire life cycle of electrical equipment according to IPCC

Each year, the IPCC publishes emissions data for production, operations, disposal and recycling, based on reporting by national authorities. These are compared in Figure 22 in the European context (including Turkey). This shows that emissions are decreasing in the EU as a whole, including in the European countries with the highest emissions. On the other hand, overall emissions from electrical equipment have risen sharply in Turkey since the UNFCCC began monitoring in 1995. One reason for this could be European manufacturers' outsourcing of production capacities to Turkey. Furthermore, assumptions and methodologies for monitoring in the individual countries are difficult to compare.

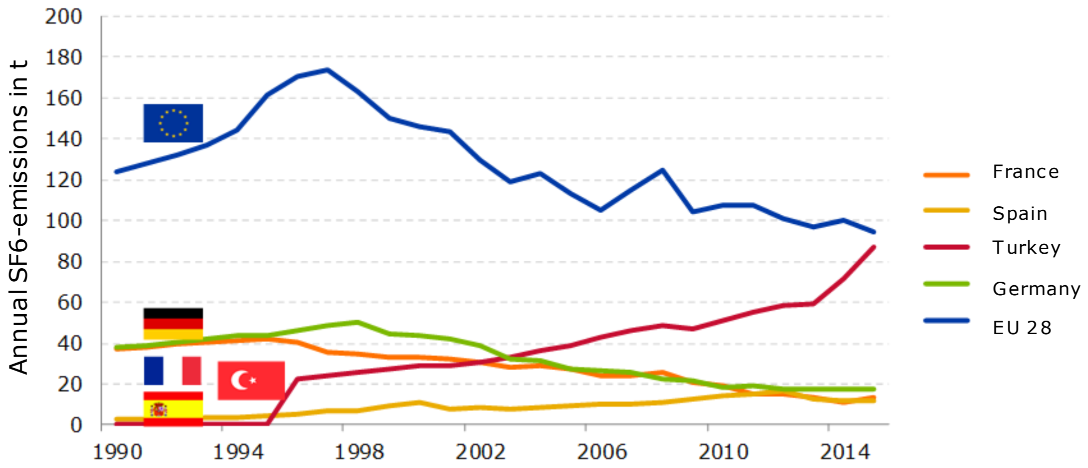

Figure 23: Development of SF_6 emissions in the electrical industry (2.F.8) of three European production countries and the EU as a whole, compared with emissions from Turkey
Source: Own research based on [UNFCCC, 2016]

Figure 24 shows a reduction of emissions in the USA, Japan and the EU. Despite significant savings, particularly in the operation of installations, emissions in the USA are much higher than those in Europe.

Emission rates are unknown for most Asian countries. However, according to manufacturers, these countries generate about 40% of worldwide emissions (see also [Fang et al., 2013a; Fang et al., 2013b]).

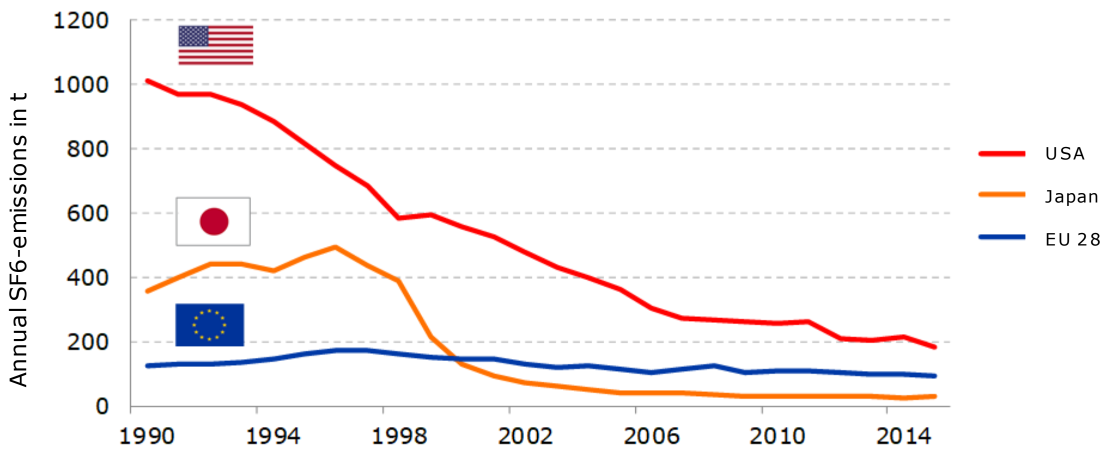

Figure 24: Development of SF_6 emissions from the electrical industry (2.F.8) in the USA versus the EU
Source: Own research based on [UNFCCC, 2016]

6 Comparison of SF_6 and SF_6-free technologies

This section describes the current state of developments in SF_6 and SF_6-free systems. It starts with a general technical introduction to the various options (solids, liquids, gases, vacuum). This is followed by a description and comparison of SF_6 products and SF_6-free technologies available on the market. The aim of this section is to show which applications and voltage levels are covered today by SF_6 and the extent to which alternatives can take on this role. To do this, in addition to the parameters specified in section 4.2, further criteria for evaluating the equipment listed in section 4.3 are specified. In view of these criteria, we compare commercially available SF_6-containing and SF_6-free products manufactured by large- and small-scale European producers.

Compared specifically with new, alternative gases, the development of SF_6 technologies is ahead by several decades and, consequently, SF_6 products have a very wide market range. In this report, the term 'dry air' (insulation medium in GIS at > 1 bar), as defined in , is used as alternative gas, while atmospheric air (insulation medium in AIS at atmospheric pressure) is termed simply as 'air'. The GWP of the mixed gases was calculated based on the formula in the EU Regulation 517/2014 (F-Gas Regulation) and is a mass-based variable (see Appendix 0). When comparing the GWP of different insulation gases, it must be taken into account that an installation filled with a light gas contains a lower gas mass than with a gas of higher molar mass (at the same fill pressure). As such, the gas mixture g[3] is lighter by a factor of ~2.5-2.9 than SF_6 and, hence, an installation at the same fill pressure contains a gas volume that is lower by the same factor and correspondingly emits fewer greenhouse gases.

SF_6-free products currently have a low market coverage (e.g. up to the highest voltage levels). This may shift in the near future, depending on the investment or marketing strategies of producers as well as customer behaviour.

Decomposition products

Under partial discharge and arc conditions in gases, a partial decomposition of synthetic gas molecules occurs. A gas must be stable in the long term to be able to perform many switching operations. SF_6 is known for its almost complete recombination after switching [Mosch et al., 1979]. In gas mixtures of alternative gases (C5-PFK, C4-PFN) with natural gases (CO_2, N_2, O_2), the recombination capacity is not as good as in SF_6 [Preve et al., 2016; Pohlink et al., 2016]. In all gases, including SF_6, switching leads to toxic decomposition products, with the quantity depending on the type of gas and increasing with the number of switching operations [Chu, 1986; Dervos und Vassiliou, 2000; Powell, 2002; Preve et al., 2016; T&D Europe, 2015b]. Dry air has advantages in terms of long-term stability and toxic-organic decomposition products due to the absence of carbon-containing F-gases [Lutz et al., 2017]. SF_6 becomes toxic especially when combined with moisture (water) and solid burn-off products, copper, wolfram or Teflon. A switch is a closed system and only in extremely rare arcing cases do the escaped gases include decomposition products. Furthermore, the relatively rapid dilution of the exiting gas by diffusion and convection results in low concentrations. Two accidents involving personal injury from SF_6 decomposition products have been documented [Pilling und Jones, 1988; Kraut und Lilis, 1990]. High-voltage switchgear is usually built outdoors and for indoor switchgear, suitable gas detection can be installed.

At the medium-voltage level, this is more difficult as switchgear installations are very numerous and installed close to public spaces, but the fill quantities are much lower than in the high-voltage installations. Inside buildings, this risk can be counteracted by adequate ventilation and generally by appropriate safety standards for the specialist personnel.

Latest investigations on decomposition products in MV and HV installations:

- AirPlus in MV load-break switch (buffer switch, ABB) [Hyrenbach et al., 2017]:
  - 100 successful interruptions showed no significant deterioration of the gas and no toxic by-products were detected.
  - No change in pressure was observed and gas samples showed only traces of decomposition products.
  - The zeolite desiccant (installed in real GIS applications) even absorbed some of the decomposition products.
- AirPlus in HV circuit-breaker (ABB) [Claessens, 2017]:
  - Status of pilot installation at ewz/Zurich North (October 2017): Fault-free operation of UW Oerlikon since August 2015. No measurable decomposition of fluorine ketones to date.
  - The decomposition products in the circuit-breaker are largely uncritical.
  - Existing safety measures for dealing with used SF_6 are completely sufficient.
  - The 'ageing' of the insulating gas due to decomposition of C5-PFK is not a problem for typical GIS tank sizes.
  - With correct dimensioning, the service life of the switching chamber is still determined by the nozzle and contact erosion
- g^3 in HV voltage transformer [Gautschi 2017]:
  - No gas decomposition or partial discharge activity detected
- Ageing behaviour in Clean Air, C5-PFK and C4-PFN mixtures [Lutz et al., 2017]:
  - The use of gas mixtures containing carbonaceous F-gases (C5-PFK, C4-PFN) may affect the service life of gas-insulated equipment: less impairment for pure insulation applications (e.g., buried GIL systems), more impairment for use as an arc-extinguishing medium
  - Gas mixtures with C5-PFK show thermal ageing, material incompatibilities
  - Clean Air is a gas mixture with excellent long-term stability and no toxicological restrictions

Table 11 below gives an overview of the most important properties of SF_6 compared to alternative gases. In addition to the alternatives presented in the table, other alternative gases are discussed, but these do not appear as options for pilot installations.

Table 11: Overview of the properties of SF_6 and selected alternative gases

Sources: *[NIST, 2016], **[IPCC, 2013], *[3M, 2015a]**

	Sulphur hexafluoride SF_6	Perfluoroketone C5-PFK	Perfluoronitril C4-PFN	Dry air N_2/O_2
Trade name	SF_6	Novec 5110	Novec 4710	Nitrogen/oxygen
Chemical formula	SF_6	$C_5F_{10}O$	C_4F_7N	N_2, O_2
Boiling point	-64 °C*	+27 °C [3M, 2015b]	-4.7 °C***	-196 °C, -183 °C*
CAS number	2551-62-4	756-12-7	42532-60-5	
Atmospheric residence time	3,200 years**	16 days [3M, 2015b]	22 years***	
GWP	22,800	<1 [3M, 2015b]	1490***	0
Properties of gas mixture				
Trade name/ product name		AirPlus (ABB)	g^3 (GE)	Dry Air or Clean Air (Siemens)
Gas mixture in usage	usually pure (100%) in cold regions as mixtures: ~60/40% N_2/SF_6 ~50/50% CF_4/SF_6 GIL:20% SF_6 in N_2	MV-GIS: ~7...14% C5-PFK in air HV GIS: ~6% O_2 in N_2	~4%...10% in CO_2	~20% O_2 in N_2
Typical minimal working temperature	pure: <-30 °C in N_2 or CF_4: <-50 °C	MV: -15 °C…-25 °C HV: +5 °C…-5 °C	-30 °C...-10 °C	<-50 °C
GWP of gas mixture (calculated according to [EU, 2014])	100% SF_6: 22,800 20% SF_6 in N_2: 12,900 50% SF_6 in CF_4: 16,720 (GWP CF_4:6.630)	For all mixtures ≤ 1	230…490	0
Average molar mass (g/mol)	100% SF_6: 146 20% SF_6 in N_2: 52 50% SF_6 in CF_4: 117	MV-GIS: ~45…62 HV GIS: ~57	50…59	29

6.1 Medium-voltage technologies

Switchgear for primary and secondary distribution

SF_6 switchgear for medium-voltage covers all the usage scenarios in the European power network described in section 4.4. Table 12 shows the most important variants of insulating and arc-quenching media available in the market for switchgear or pilot projects for primary and secondary distribution. Table 13 and Table 15: show examples of the characteristics of products from European producers in the 24kV category, which is important to the market.

Table 12: Variants of new metal-encapsulated/metal-clad switchgear for primary and secondary distribution

Source: Own research

Name	Type	Insulation	Load-break switch	Circuit-breaker
GIS	sealed	SF_6	SF_6	SF_6
GIS	sealed	SF_6	SF_6	Vacuum
GIS	sealed	SF_6	Vacuum	Vacuum
GIS	sealed	~7-14% C5-PFK in air	Vacuum	Vacuum
GIS	sealed	Dry Air	Dry Air	Vacuum
AIS	open	Air	SF_6	SF_6
AIS	open	Air	SF_6	Vacuum
AIS	open	Air	Air	SF_6
AIS	open	Air	Air	Vacuum
Solid-insulated	sealed	Solid (+air)	Vacuum	Vacuum
Fluid-insulated	sealed	Fluid	Vacuum	Vacuum

Unlike in primary distribution, switchgear for secondary distribution (including RMUs) consist of sections in which SF_6 is used in technically relatively simple load isolation switches only for separation, grounding and switching of operating currents, but not for switching short-circuit currents. According to various manufacturers, vacuum load-break switch designs are 30-100% more complex and more expensive than SF_6 load-break switches which have a very simple structure. This rise in cost is qualified by the increasing use of secondary technology in the course of increased grid automation (electronics for control, monitoring, metering, etc.), which can account for up to 50% of the total costs in higher-quality switchgear.

AIS for primary distribution are produced by most manufacturers and are a good option, when minimum space requirements are not a main criterion. Solid-insulated switchgear could be the same size or even more compact than its SF_6 counterparts. Two large representatives of this insulation technology, Eaton and Schneider Electric, rely on the variants of 'classical' (Eatons Xiria) or 'shielded' (Schneiders Premset) insulation with solids mentioned in section 4.2.

Both these manufacturers consider the market for switchgear up to higher rated voltages (> 24kV) and currents to be too small to justify the costs of investment in them. On the other hand, according to the same manufacturers, the stronger electrical and thermal loads at higher voltage and current levels are technically feasible using solid materials for insulation. Additionally, it is often difficult to compete with the low production costs of SF_6 installations manufactured in large numbers. This is also attributable in part to the high procurement costs of different types of castings which are necessary for the production of cast resin components. These costs can partially be offset by high production numbers, thus lowering total production costs.

Cellpack uses the synthetic ester 'Midel 7131' as insulation fluid, thus enabling highly compact installations. MIDEL 7131 has been classified as not hazardous to water by the German Federal Environmental Agency. As a relatively small manufacturer, Cellpack focuses on the major market of secondary distribution up to 24kV, although switchgear for primary distribution at higher voltage levels would be possible, according to manufacturer's specifications.

The alternative gas mixture Airplus is used in primary as well as secondary installations. Airplus is used only for insulation, while the switching (including load switching) is done in a vacuum. Grid operator EWZ in Zurich, Switzerland has installed the first pilot of a ZX2 Airplus from ABB (50 functional units, 22kV, 1,600 A for the supply feeder and 2,000 A for the busbar). In 2016, NetzeBW commissioned the second pilot in Baden-Württemberg, Germany. The ZX2 installation was launched on the market as a product at the end of 2016. It is a purely indoor installation, with a minimum operating temperature of -5 °C required by IEC 62271, though it can be operated at temperatures as low as -15 °C according to the manufacturer. The construction of the ZX2 AirPlus switchgear is based on the SF_6 switchgear ZX2, but minor modifications had to be made because of different parameters, such as the dielectric behaviour, heat transfer capability, reaction properties and material compatibility. Because of the presence of oxygen, the surfaces of the primary circuit had to be coated with silver, resulting in significant additional costs. The current ZX2 Airplus portfolio ranges up to rated voltages of 36kV and measured currents of 2,000A (compared with 40kV and 3,000 A for ZX2 with SF_6). The manufacturer has announced that it intends to expand the portfolio to higher ratings over the next 3-4 years. The SafeRing Airplus 24kV RMU is based on the SafeRing Air which uses air as its insulation gas and is limited to 12kV. The minimum operating temperature of this secondary-distribution installation is -25 °C. Currently, some segments cannot be covered by AirPlus products, such as the higher-rated, short-term power frequencies required in the US for 36kV plants (80kV ANSI versus 70kV IEC) or in China/former CIS (80kV).

Table 13: Comparison of different MV switchgear for primary distribution (circuit-breaker unit) using examples from European producers (24kV variants or similar)
Source: Own research based on product sheets

Switchgear name	Eaton Power Xpert UX	Eaton Power Xpert FMX	Siemens NXAIR	Siemens 8DA10	ABB ZX2	ABB ZX2 Airplus	ABB Unigear ZS1	Schneider GMA	Ormazabal Cpg.0
Picture									
Insulation	Dry Air + Solids	Dry Air + Solids	Air	SF_6	SF_6	AirPlus	Air	SF_6	SF_6
Circuit-breaker	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum
Rated voltage (kV)	24	24	24	24	24	24	24	24	24
Rated current (A)	2,500	2,000	2,500	2,500	2,500	1,600	2,500	2,500	2,500
Width (mm)	1,000	1,000	1,000	600	600-800	600-800	1,000	800	600
Depth (mm)	1,570	1,450	1,350-1,650	1,625	1,860	1,860	1,700	1,280-1,400	1,364
Height (mm)	2,320	2,100	2,300	2,350	2,300	2,300	2,325	2,200	2,420

Table 14: Comparison of different MV switchgear for primary distribution (circuit-breaker unit) using examples from selected European producers (24kV variants or similar)

Source: Own research based on product sheets

Switchgear name	Eaton Xiria E	Schneider Premset	Schneider SM6	Ormazabal gae	Siemens 8DJH	ABB UniSec
Picture						
Insulation	Air + Solid	Solids	Air	SF_6	SF_6	Air
Circuit-breaker	Vacuum	Vacuum	Vacuum or SF_6	Vacuum	Vacuum	SF_6
Load-break switch	Vacuum	Vacuum	Vacuum or SF_6	SF_6	SF_6	SF_6
Rated voltage (kV)	24	17.5	24	24	24	24
Rated current (A)	630	1,250	630-1,250	630	630	630-1,250
Width (mm)	500	375	625-750	600	430	750
Depth (mm)	600	910	400-830	730-851	775	1,070-1,300

Table 15: Comparison of different secondary-distribution MV ring-cable switchgear (consisting of 1 circuit-breaker unit and 2 ring-cable units) from European producers (24kV variants or similar)

Source: Own research based on product sheets

Switchgear name	Eaton Xiria	Cellpack ECOS-C (-25°C)	ABB SafeRing AirPlus	ABB SafeRing	Ormazabal ga	Siemens 8DJH	Schneider RM6
Picture							
Insulation	Air+Solid	synth. Ester	AirPlus	SF_6	SF_6	SF_6	SF_6
Circuit-breaker	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	SF_6
Load-break switch	Vacuum	Vacuum	Vacuum	SF_6	SF_6	SF_6	SF_6
Rated voltage (kV)	24	24	24	24	24	24	24
Rated current (A)	630	630	630	630	630	630	630
Total width (3 units) (mm)	1,110	890	1,021	1,021	980	1,050	1,186
Depth in (mm)	600	1,040	765	765	730-851	775	670

Table 16 gives an overview of areas of application in which alternatives are already available, the level of technological advancement and the areas for which no alternatives are possible/implemented. Technologies with generally acknowledged technical disadvantages or concerns related to safety and the environment (e.g. oil or compressed air circuit-breakers) are not considered here.

Table 16: Overview of SF_6-free MV electrical equipment that requires insulating and arc-quenching media
Source: Own research based on product sheets

Insulation medium	Air (AIS)	SF_6-free gas mix	SF_6-free gas mix	Solids	Fluid
Arc-quenching medium	**Vacuum**	**Vacuum**	**SF_6-free gas mix**	**Vacuum**	**Vacuum**
MV switchgear (primary distribution)	implemented, >5 years on the market (up to 36kV)	implemented, < 5 years on the market (up to 24kV)	not implemented	implemented, >5 years on the market (up to 36kV)	not implemented
MV switchgear (secondary distribution)	implemented, >5 years on the market (up to 12kV)	implemented, < 5 years on the market (up to 24kV)	not implemented	implemented, >5 years on the market (up to 24kV)	implemented, >5 years on the market (up to 24kV)

Generator circuit-breakers

Modern SF_6 generator switches range up to operating voltages of 31.5kV and can switch rated currents up to 28kA and short-circuit currents of up to 250kA [Cavaliere und Kreisel, 2013]. As already shown by existing installations in section 5.2, SF_6-free vacuum technology exists up to 24kV and 100kA. Currently, no alternative-gas products are available for generator circuit-breakers.

6.2 High-voltage technologies

Gas-insulated switchgear

HV GIS containing SF_6 has been operated around the world since the 1960s. Today, SF_6 GIS ranges up to rated voltages of 1,100kV and currents of 8,000A (mainly in China). The major market for HV GIS lies in the voltage range up to 170kV[13]. SF_6-free GIS has recently become available in this market sector in the form of pilot installations (ABB GLK-14 with AirPlus) and products (GE with F35 and Siemens 8VN1 with Clean Air). Table 17 compares important parameters for SF_6-free GIS available on the market with analogous SF_6 products.

[13] Electrical equipment with a rated voltage of up to 170kV is operated exclusively in the high-voltage level with a rated voltage of 110kV. The nominal voltage in German transmission networks (extra-high voltage) is 220kV and 380kV.

Initial experiences with 170kV-GIS (model GLK-14 from ABB), which contains AirPlus, have been gained since 2015 in a pilot installation consisting of 8 functional units in Zurich (EWZ). The electric strength of the mixture used is lower than that of SF_6 at the same pressure. For this reason, the design of the GLK-14 GIS is based on the design of the ELK-14C operated with SF_6, which is designed for higher voltages (245kV) and currents. Accordingly, the dimensions of 170kV alternative-gas GIS are significantly larger than those of 170kV SF_6 GIS ELK-04 C. Due to the relatively high boiling point (+27 °C) of C5-PFK, the gas mixture starts liquefying at ambient temperatures of -5 °C to +5 °C, which rules out outdoor application of the gas mixture unless additional heating is applied.

The 145kV g^3 GIS is a product from GE, based on the SF_6 model F35 and will be commissioned in 2017 at two locations (substation Axpo Switzerland and a transformer station in Berlin). The g^3 GIS operates under excess pressure of approx. 2 bar in contrast to SF_6 GIS. The low boiling point of C4-PFN compared with C5-PFK also allows for outdoor applications.

The 145kV GIS from Siemens uses a vacuum circuit-breaker in contrast to the other SF_6-free installations. The disconnection/grounding takes place in Clean Air. The model is based on the SF_6 installation 8DN8-6, which is designed for a rated voltage of 170kV. Additionally, the clean air installation has a lower rated current than SF_6 installations, which can be attributed to the better cooling properties of SF_6.

Table 17: Comparison of different HV SF_6 and alternative-gas GIS from European producers (145kV variants or similar)

Volume is defined as length x width x height of a standardised GIS double busbar unit

Source: Own research based on product sheets

Switchgear name	ABB ELK-14C	ABB GLK-14	ABB ELK-04	GE F35 g³	GE F35	Siemens 8VN1	Siemens 8DN8-6
Picture							
Insulation	SF_6	AirPlus	SF_6	g³	SF_6	Clean Air	SF_6
Circuit-breaker	SF_6	AirPlus	SF_6	g³	SF_6	Vacuum	SF_6
Rated voltage (kV)	253	170	170	145	145	145	170
Rated current (A)	3,150	1,250	4,000	3,150	3,150	3,150	4,000
~Volume (m^3)	21	21	17-19	7	7	18	18
~Weight (tons)	6	6	2.4°-°3.8	2.5	2.5	5	5
Minimal temperature (°C)	-25	-5 to +5	-30	-25	-30	-50	-30

HV circuit-breakers for air-insulated switchgear

SF_6-free circuit-breakers from European manufacturers exist only in the form of live tank variants (see section 4.3.2) and only for rated voltages up to 145kV (see Table 18). For higher voltages, currently only SF_6 switches are available.

Table 18: Comparison of different SF_6 and SF_6-free live tank circuit-breakers from European manufacturers for open-air HV switchgear (> 52kV)
Source: Own research based on product sheets

	ABB LTA 72D1	ABB LTB D1/B	GE GL 309	GE VL 109 (Pilot plant)	Siemens 3AV1
Insulation	CO_2	SF_6	SF_6	Dry Air	Clean Air
Circuit-breaker	CO_2	SF_6	SF_6	Vacuum	Vacuum
Rated voltage (kV)	72.5	72.5	72.5	72.5	72.5
Rated current (A)	2,750	3,150	3,150	2,000	2,500
Minimal temperature (°C)	-50	-30	-40	<-30	-30

HV instrument transformers for air-insulated switchgear

Conventionally, HV instrument transformers have been insulated with SF_6, oil or oil/paper and can be found with these insulation media into the highest voltage levels. For current transformers, there are also products (FOCS-FS by ABB, CISO by GE) current measurements of which are not based on the electrical transformer principle, but instead on an optical method using glass fibre connections. For this reason, they do not need any oil or SF_6 insulation and are available up to the maximum operating voltages. The weight of instrument transformers insulated with oil or oil/paper is not always higher than that of transducers insulated with SF_6. Recently, a 245kV current transformer with the C4-PFN/CO_2 (g^3 by GE, -30° C min. temperature) has been launched on the market, six units of which are currently in operation in Germany (in suburbs of Frankfurt and Lehrte). No major modifications were necessary during the manufacture of this g^3 current transformer, which was originally designed with SF_6 insulation. Only the seals were replaced with a compatible material widely used in other areas for CO_2. According to manufacture specifications, higher operating voltages appear to be possible in the future using the C4-PFN/CO_2 mixture. Siemens will start to operate voltage and current transformers with Clean Air insulation in mid-2018 at a 110kV transformer station (Nördlingen, Germany).

HV GIL

Siemens, with a mixture of 20% SF_6 in N_2, as well as GE with the same mixture and recently also with the g^3 alternative are the only European suppliers of GILs. GE offers g^3 GILs up to the extra-high voltage levels (see Table 19). There are two existing g^3 GIL projects (Sellindge, UK, since 2016, and Kilmarnock, UK, since 2017). To ensure a minimum temperature of -25 °C, a lower excess pressure must be used compared to an SF_6 GIL.

This results in 8% more material consumption. In existing SF_6 GILs, SF_6 cannot be replaced directly by the g^3 mixture, because technical modifications of seals, absorbers, fill valves and monitoring devices are necessary. In GILs, potential savings due to SF_6-free alternatives are especially high because of the high quantities of SF_6 used (for example, for the 100m-long GIL section in Sellindge, a quantity of 1.6 tons of SF_6 would be needed).

Table 19: Comparison of different gas-insulated lines (GIL) from European producers
Source: Own research based on product sheets

	Siemens GIL	GE GIL SF_6	GE GIL g^3
Insulation	SF_6/N_2	SF_6/N_2	g^3
Rated voltage (kV)	up to 550	up to 800	up to 800
Rated current (A)	up to 5000[14] *	up to 6,300	up to 6,300
Minimal temperature	-30 °C	-30 °C	-25 °C

Table 20 and Table 21 give an overview of areas of application in which alternatives are already available, the level of technological advancement and the areas for which no alternatives are possible/implemented. Technologies with generally acknowledged technical disadvantages or concerns related to safety and the environment (e.g. oil or compressed air circuit-breakers) are not considered here.

Table 20: Overview SF_6-free HV equipment (voltage level up to 110kV) that require insulating and arc-quenching media
Source: Own research based on product sheets

Insulation medium	SF_6-free gas mix	SF_6-free gas mix	Solids	Fluid
Arc-quenching medium	**Vacuum**	**SF_6-free gas mix**	**Vacuum**	**Vacuum**
HV switchgear	implemented, <5 years on the market[15]	implemented, <5 years on the market[15]	not implemented	not implemented
HV circuit-breaker, Live Tank	up to 145kV implemented, <5 years on the market[15]	up to 72.5kV implemented, <5 years on the market[15]	not implemented	not implemented
HV circuit-breaker, Dead Tank	not implemented	not implemented	not implemented	not implemented

[14] Max. realised rated current of 8000 A at 550kV.
[15] The term 'on the market' includes switchgear that has been type-tested and for which product information is available on the manufacturer's website. This term can include pilot installations, prototypes as well as products.

Table 21: Overview of SF_6-free HV equipment that require only an insulation medium

Source: Own research based on product sheets

Insulation medium	Alternative gas	Solids	Fluid/Oil	Other technology
HV voltage transformer	implemented, <5 years on the market[15]	implemented, >5 years on the market[15]	implemented, >5 years on the market[15]	
HV current transformer	implemented, <5 years on the market[15]	implemented, >5 years on the market[15]	implemented, >5 years on the market[15]	Optical
HV bushing	not implemented	implemented, >5 years on the market[15]	implemented, >5 years on the market[15]	
HV-GIL	implemented, <5 years on the market[15]	not implemented	not implemented	Overhead line, cable

7 Current regulatory framework on SF_6 in electrical equipment

The equipment and technologies described in the previous chapters are subject to various specifications set by technical standards and regulation. Along with the adherence to specifications, performance requirements and safety measures, emissions must be reduced and personnel must be protected. The following sections give an overview of regulations currently applicable in Europe. A differentiation is made between commitments applicable to all EU member states (these include EU regulations, internationally applicable standards and the European emissions trading system), as well as measures taken by individual member states. The commitments of the individual states differ heavily with respect to ambitions and scope. Using selected countries as examples, the regulatory nuances and the results of voluntary commitments, taxes and prohibitions are compared.

The overview describes the current regulatory context for switchgear and 'other electrical equipment' containing SF_6. With the introduction of new gas mixtures, an amendment of technical standards and regulations is also expected. The standardisation committee IEC AHG5 has created an inventory of the standards that must be revised as a first step.

7.1 International and European specifications

In the first section, we review measures that concern the regulatory framework and apply equally to all EU member states. EU regulations, internationally applicable standards and the European emissions trading system are described and evaluated.

7.1.1 Laws, regulations and guidelines

European regulations form the framework for manufacturers and users of gas-insulated electrical equipment in the European Union. After being enacted, a regulation immediately becomes legally binding in the member states. The following three regulations are especially relevant for manufacturers and users.

EU regulation No. 517/2014: Since 1 January 2015, the revised regulation (EU) No. 517/2014 (F-Gas regulation) is applicable in the EU. It regulates the use of the fluorinated greenhouse gases HFKW, FKW and SF_6. It replaces the regulation (EC) No. 842/2006 on certain fluorinated greenhouse gases. The requirements of the regulation for the use of F-gases include leakage checks, necessary measures taken by manufacturers for the best possible limitation of emissions (e.g. improvement of the leak-tightness of containers), identification of electrical switchgear and recycling requirements. Furthermore, regulations also exist for certification and reporting.

Bans on the usage and market entry of products are enacted if technically feasible, cost-effective and climate-friendly alternatives exist. Especially for the new secondary medium-voltage switchgear, it will be assessed by 1 July 2020 whether economical, technically feasible, cost-effective, energy-efficient and reliable alternatives exist [EU, 2014]. Until 31 December 2022, all other applications are to be assessed with respect to the technical feasibility and cost-effectiveness of alternatives.

EU regulation 1907/2006 REACH: This regulation has been in effect since 2007 and applies to manufacturers or importers, who manufacture products as a whole or as part of a mixture with more than one ton per year in the EU or import these into the EU [EU, 2012]. Each manufacturer or importer requires a registration number as well as a technical dossier for the products covered by REACH [Umweltbundesamt, 2016]. Furthermore, manufacturers of gases are obligated to summarise the physical and chemical properties, information about the handling and possible risks of SF_6 in a safety data sheet in accordance with 1907/2006/EC (REACH), Annex II.

EU regulation (EU) No. 166/2006 EPRTR: This regulation mandates that operators of specific industrial plants (such as production sites of chemicals and F-gas destruction plants) report emissions to the European Commission. For SF_6, any emissions of 50kg per year or higher must be reported.

German Environmental Statistics Act (UStatG): Section 10(2) of the German Environmental Statistics Act mandates reporting for SF_6 and NF_3. This reporting forms the basis for publications on SF_6 by the German Federal Statistics Office. The data collection keeps track of volumes and, in part, intended uses of gases by companies that manufacture sulphur hexafluoride or nitrogen trifluoride, import or export them, or supply them domestically in volumes greater than 200kg per year. Data collection on SF_6 pursuant to section 10(2) was carried out in 2006 for the first time. Data collection on NF_3 started in reporting year 2015.

7.1.2 Technical norms and standards

In general, norms and standards can be considered part of industrial self-regulation and are not legislative in nature. Nevertheless, many governments and industrial associations directly or indirectly demand adherence to technical standards. As a result, de facto conformity to standards exists, as if the standards were legally mandated.

Electrical equipment that use switching gases are subject to numerous international, European and national standards for specifications, performance requirements and safety measures. The most important internationally applicable standards concerning electrical equipment that uses SF_6 are listed in Table 22.

Table 22: Relevant international standards for electrical equipment using SF_6
Source: Own research based on the standards reviewed

Standard	Description
IEC 62271-1	High-voltage switching devices and switchgear; general regulations incl. leakage rates
IEC 62271-102	High-voltage switching devices and switchgear: Alternating current disconnecting switches and grounding switches
IEC 62271-103	High-voltage switching devices and switchgear: Load switches for rated voltages above 1kV up to and including 52kV
IEC 62271-105	Alternating current fused load-breaks with a rated voltage above 1kV up to and including 52kV
IEC 62271-200	Metal-encapsulated, alternating current switchgear with a rated voltage above 1kV up to and including 52kV
IEC 62271-203	Metal-encapsulated, high-voltage switching devices and switchgear; general regulations incl. leakage rates
IEC TR 62271-4	High-voltage switching devices and switchgear; Handling methods when dealing with SF_6 and its mixed gases
IEC 61869-1	Instrument transformers; general regulations incl. leakage rates
IEC 60376	Specification of the technical grade of SF_6 for use in electrical equipment
IEC 60480	Guidelines for testing and handling SF_6 from electrical equipment and specifications for reuse

The introduction of new gas mixtures makes it necessary to revise the existing standards. It is unclear whether existing standards can be extended to alternative gases or whether a new standardisation process must be initiated. The IEC work group 'AHG 5 - Alternative Gases' has investigated the introduction of new gases and their effects on standards for switchgear. A final report is available [IEC, 2016]. The work group 'Gases for Switchgear' from T&D Europe has also prepared for the standardisation process with a technical guideline for validating alternative gases in electrical equipment [T&D Europe, 2015b].

7.1.3 Market framework conditions

The European emission trading system (EU-ETS) was launched in 2005. This system abides by a 'cap and trade' principle. The trading system encompasses the three gases CO_2, N_2O and PFC from the energy-consuming industry, also integrating air traffic from 31 countries (EU28 as well as Iceland, Liechtenstein and Norway), thus representing 45% of all greenhouse gas emissions in these countries. Until 2020, F-gases other than PCF (including SF_6) and other sources of emissions fall outside the scope of the EU-ETS [EC, 2016].

SF_6 is already included in emissions trading systems in other countries and regions. Examples of these emissions trading systems have been implemented in South Korea, California and Ontario, Canada [ICAP, 2016].

7.2 Country-specific regulatory framework conditions

Overarching European measures apply equally to all EU member states. However, national ambitions for reducing emissions vary from one country to another. As a result, there are very different framework conditions within the EU for the use of SF_6 in electrical equipment. Using selected countries as examples, we compare the various framework conditions and their effects below.

7.2.1 Voluntary agreements and commitments

In Germany, France, Norway, Spain and Switzerland, the governments have signed voluntary agreements with the industry for minimising SF_6 emissions. These agreements vary in terms of timeframes and set targets. Table 23 gives an overview of the goals of the voluntary commitments as well as their results as reported by the industry. The time period of application for the voluntary commitment has been exceeded in some cases. Current information about the ongoing status of voluntary commitments is not available.

Table 23: Overview of voluntary commitments between the industry and national governments
Source: Own research based on [Benner et al., 2012; VDN et al., 2005; ABB et al., 2012; T&D Europe, 2011; SOLVAY et al., 2005, 2005]

Country	Germany	France	Spain	Norway	Switzerland
Time of the voluntary commitment	May 2005	2004	March 2008	March 2002	April 2012
Time period of application	2004 – 2020	1995 - 2012, no extension after 2012	2008 - 2012, extended until at least 2021	2008 - 2010, no extension after 2010	-
Goals	Restriction of the overall emissions to 17t SF_6/a by 2020	Purely qualitative specifications	Emission reduction by a total of 330,000t CO_2-e between 2006 and 2012	Emission reduction by 30% between 2000 and 2010	Emissions from the manufacture and operation of HV and MV plants < 4t SF_6/year
Successes according to the industry (T&D Europe)	46% total reduction between 2004 and 2014. 50% reduction in emissions from production	50% reduction in emissions from production between 1995 and 2009.	30% total reduction between 2006 and 2009.	50% total reduction between 2000 and 2010.	75% reduction of emission rates in use between 2004 and 2016

7.2.2 Taxes and duties

In some countries, SF_6 in electrical equipment is/has been subject to taxation. The amount of tax is up to €100/kg SF_6. Based on the examples of Denmark, Slovenia, Spain and Norway, we describe and compare planning and implementation of taxes and their effects.

In **Denmark**, a tax on the import of fluorinated gases has been in effect since 2001. Gases with the highest climate relevance are also taxed at the highest rate. A tax of DKK600/kg (€80/kg) applies to SF_6. The tax includes a number of applications, including insulation gas in electrical installations. One exception is switchgear insulated with SF_6 ≤ 36kV in power distribution [SKAT, 2016]. Apparently, the tax has raised awareness of the consequences of SF_6 among manufacturers and users of electrical equipment [Nordic Council of Ministers, 2007]. Furthermore, it has prompted a discussion about alternative gases and led to improvements in recycling. However, according to the UNFCCC, emissions have increased in absolute terms in the years since the introduction of the tax [UN, 2014a].

In **Slovenia**, a tax was imposed in 2009 on the production and import of SF_6 and 'other electrical equipment' containing fluorinated gases. The amount of the tax is based on the climate relevance of the gases as well as their application. From 2009 to 2013, the price per ton of CO_2-e has increased continuously. In 2013, it was €14/t of CO_2-e or €330,000/t of SF_6. For the first filling of installations with SF_6, the tax only applied to 5% of the fill volume. For maintenance and refilling, the tax applied to 100% of the volume. Because of the complaints from the industry, the rate was reduced significantly starting with 2014. In 2015, it was only €3.50/t of CO_2-e. Since April 2016, the payment of the taxes is no longer due [Republic of Slovenia Ministry of Finance, 2016; Duncan Brack, 2015; Schwarz et al., 2011].

Since January 2014, **Spain** has taxed F-gases with a GWP > 150, including SF_6. The tax amount is €20/t CO_2-e. However, this is capped at €100/kg [Boletín oficial del estado, 2013]. The tax applies to the refilling of SF_6 in switchgear, so it only affects operators of the installations. The first filling/production and the import of switchgear are excluded from the tax [AFBEL, 2013].

In **Norway**, a tax on SF_6 was discussed prior to the voluntary agreement between the Environment Ministry and the Norwegian Emission Control Authority. After discussions with the electrical industry, the tax was rejected because of competitive disadvantages in the global market. Instead, a voluntary agreement was established [Schwarz et al., 2011].

7.2.3 Ban on SF_6-filled MV installations in Lower Saxony's government buildings

Since March 2017, a decree and an ordinance has taken effect in the German state of Lower Saxony prohibiting the use and purchase of SF_6-filled medium-voltage installations in future new construction and renovation projects by the state government. According to the government's own reports, the ban is consistent with the goals of the Lower Saxony Climate Law (Nds KlimaG), which aims to reduce the federal state administration's greenhouse gas emissions by 70% (base year 1990) by 2050. Exceptions are granted in certain cases. However, the use of air- and solid-insulated plants is possible in the most cases, according to the Highest Financial Directorate of Lower Saxony, even regarding cost-effectiveness.

8 Views of Manufacturers and Operators

During this project, a number of interviews were conducted with manufacturers and users. Furthermore, discussions were held with representatives of industrial associations. The section below gives an overview of the breadth of different positions and takes stock of opinions held within the industry. The interviews reflect a diversity of views about SF_6 alternatives, ranging from very critical to positive. The first section consciously avoids presenting possible majority opinions or a median.

The second section lists consolidated viewpoints of the relevant industry associations (Work Group SF_6, ZVEI, FNN and T&D Europe). It also provides an overview of relevant publications and positions taken by the various groups and associations. The third sections of the chapter summarises essential parts of the discussion and outcomes from the first expert workshop, held in March 2017, from the perspective of the project team. Outcomes of the second expert workshop, held in September in Brussels on the topic of possible concepts for reducing the emissions and use of SF_6 are included in chapter 9. Furthermore, the minutes from the second expert meeting can be found on the UBA's project website (see the link in the footnote[16]).

The interviews and technical discussion focussed on electrical equipment used in the medium- and high-voltage. For medium-voltage, discussions focussed on electrical equipment with a rated voltage of up to 24kV or 36kV, since the majority of the installations operate in this voltage level.

8.1 Viewpoints based on expert interviews

The opinions below are based on various viewpoints from individual stakeholders. For the overview, we provide a table comparing critical and supportive viewpoints regarding SF_6-alternatives. We refer to the selected technical and economic aspects which reflect a very wide spectrum of opinions. Table 24 gives an overview of equipment in medium-voltage, and

Table 25 refers to equipment in high-voltage.

Especially for switchgear in medium-voltage, there are many conflicting opinions among experts. On electrical equipment in high-voltage, there is more consensus on fundamental aspects among experts, although the larger manufacturers use and develop different kinds of technologies.

[16] The UBA's project website provides information about the project and publishes presentations and minutes from the expert workshop as well as interim reports. https://www.umweltbundesamt.de/themen/wirtschaft-konsum/produkte/fluorierte-treibhausgase-fckw/anwendungsbereiche-emissionsminderung/schaltanlagen

The opinions summarised here represent an inventory – not an evaluation - of the various positions expressed. Admittedly, the comparison in the table presents a shortened, somewhat condensed formulation of the positions and arguments. Chapters 3, 4 and 6 are indispensable in providing a proper orientation regarding the technologies discussed.

Table 24: Overview of the range of opinions on selected aspects of MV electrical equipment (focussing on equipment with up to 36kV)

Aspect	Critical opinions on alternatives	Supporting opinions on alternatives
Rated voltage and current	Generally, SF_6 alternatives currently available on the market can only be used in a limited range of parameters. This is reflected by the fact that installations are usually only available up to 24kV.	Solid- and fluid-insulated solutions can be used in most application areas (24kV installations). Manufacturers see no technical limitations for developing installations further for other specifications, at least up to 36kV. The currently limited portfolio is due to the main markets that the companies supply.
	Vacuum circuit breakers only partly fulfil the technical requirements. Their development is stuck in the initial stages.	Vacuum circuit breakers are state-of-the-art technology.
	Insulations with solids have poor current-carrying ('heat dissipation') properties.	Insulations with solids show no problems in terms of current-carrying capacity or heat dissipation.
Size and weight	In the areas of wind energy and building installations, it is impossible to achieve the necessary compact dimensions without SF_6.	Individual alternatives containing solid or liquid insulation are equally compact or even more compact than SF_6-insulated installations and can thus also be used for wind power plants and buildings installations.
Service life and long-term stability	The effect of 'sticking' in vacuum circuit breakers reduces the number of possible switching operations.	The problem of 'sticking' has already been solved many years ago through adjustments in the drive technology and electrode material.
	Users have bad experiences with insulation with solids and liquids (oil). For equipment with a service life of 20 to 40 years, there is no experience in long-term stability.	In secondary distribution, there are users with lengthy (30 to 50 years) and very positive experience using alternatives; especially solids and liquids (esters). This particularly concerns the users outside of Germany.
	Insulations with solids have to tackle the problem of partial discharge and are not reliable enough ('long-term stability').	The prejudices against insulation with solids arise from a time 30 years ago when insulations with solids were unreliable. Partial discharges are no longer a problem today; especially for shielded solid insulation systems.
Environmental effects	Only gas-insulated installations are protected against various environmental influences (pressure, dirt).	Alternatives use specific designs ('enclosed', 'encapsulated' and, particularly, 'sealed') to ensure equivalent protection. Shielded insulations with solids and liquid insulation systems are also protected against environmental influences.

Aspect	Critical opinions on alternatives	Supporting opinions on alternatives
	Replacing SF_6 with fluids shifts the problem to other problematic insulation materials. Fluids do not stand the test of time; they are hazardous to water in the event of leaks and are problematic due to their flammability.	Modern liquids (esters) are neither hazardous to water nor particularly flammable. Plus, the quantities used are very low.
	Total SF_6 emissions from the electricity industry are negligible compared with total worldwide greenhouse gas emissions and, therefore, are not worthy of discussion at all.	SF_6-free solutions can make an essential contribution to environmental protection.
Costs	Various alternatives are generally more expensive than SF_6 solutions. Switchgear in secondary distribution: 30 to 50% more expensive. Primary distribution: 10 to 25% more expensive. The further cost reduction potential is rather low due to the elaborate production processes.	Most of the additional costs are accrued due to the low number of units produced. Through scaling effects, additional costs can be pushed to under 10%. In relation to the total investment costs (primary and secondary technology) of a local grid station, the additional costs are very low. Auxiliary equipment accounts for over 50% of the investment costs.
	Operating costs across the entire service life of the installations are the same for all technologies. Investment costs for alternatives in secondary distribution are higher in comparison to SF_6 solutions.	Compared with the alternatives, SF_6 installations have higher operating costs across their service lives (reporting, gas handling). However, when evaluating economic feasibility, only investment costs are considered.
	If a complex vacuum circuit breaker has to be used instead of a simple SF_6 disconnector /earthing switch, costs will increase. Plus, a separation point inside a vacuum is technically questionable.	Vacuum circuit breaker that meet the low requirements of a disconnector can be manufactured very economically which makes them only slightly more expensive. Plus, the cost percentage of primary technology (switchgear) as a portion of overall project costs is less than 50%, which leads to a relatively low increase in total project costs.
Market acceptance	Some users tender only for specific gases (SF_6) or gas-insulated installations. Some simply reuse old tendering documents when requesting bids for new projects. This inhibits new technologies.	Sometimes, environmental aspects are included in the tendering documents.
	For users, investment costs are the decisive factor when selecting installations. This is particularly true on the mass market.	Individual user groups are willing to shoulder additional costs. For them, their public image is as important as costs.
	Customers do not buy alternatives as long as only a few products or providers exist.	Individual users have extensive experience with alternatives, particularly in the field of secondary distribution.

Table 25: Overview of the range of opinions on selected aspects of HV electrical equipment

Aspect	Critical opinions on alternatives	Supporting opinions on alternatives
Rated voltage and current	A particular challenge in HV is that SF_6 has to be replaced for switching and not only for insulation. Thus far, only prototypes or experimental devices exist for this.	Initial products with vacuum switches (offshore wind, transformer stations) up to 110kV are already being offered.
	All known alternative gases can only ever cover part of the required parameter ranges.	With a portfolio of alternative technologies, substitution is possible in the medium term.
Size and weight	In the areas of wind energy and building installations, it is impossible to achieve the necessary compact dimensions without SF_6.	In HV, there is more freedom regarding size, which makes alternatives with larger dimensions possible.
Environmental influences	Fluorinated alternative gases are not 'clean' solutions. Their GWP is low because of their faster decomposition in the atmosphere. The decomposition products are sometimes also problematic.[17]	
	The GWP of an alternative should, at most, lie within the same range as that of CO_2. PFCs have already been banned in the range of 150; this is to be expected sooner or later in power technology as well.	A reduction of 98% is substantial and adequate. The comparison with refrigerants is invalid, because it takes current refrigerants with a GWP of 230-490 as the basis for comparison, rather than a medium with a GWP of 23,500.
	The decomposition products of individual alternative gases are sometimes highly toxic and can threaten human health.	Some decomposition products of SF_6 are even highly toxic, but encapsulation prevents them from coming into contact with personnel.
	Total SF_6 emissions from the electricity industry are negligible compared with total worldwide greenhouse gas emissions and, therefore, are not worthy of discussion at all.	SF_6-free solutions can make an essential contribution to environmental protection.
Service life and long-term stability	Alternative gases decompose during normal operation, so the service life of an alternative-gas installation is lower than that of one using SF_6 and/or else	Studies conducted thus far have shown no critical ageing processes in the gases used. The maintenance cycles and service life

[17] During the discussion, reference was made to the recent publication Pohlink et al., 2016.

Aspect	Critical opinions on alternatives	Supporting opinions on alternatives
	the frequency of maintenance cycles must be increased.	are comparable to those of SF_6 installations.
Costs	Switchgear with alternative gases cannot be offered at comparable prices despite the expected scaling effect, particularly due to their product design and costly materials.	Costs for switchgear with alternative gases can be reduced to comparable prices. In HV SF_6 switchgear, costly materials are already used (e.g. silver-coated contacts).
Market acceptance	Grid operators prefer a universal, standardised solution.	In practise, diverse or even hybrid solutions are currently being used. Manufacturers can temporarily also produce different types of technology simultaneously (installations with different fillings).
	-	In the HV, mass-produced items are not used and therefore cost pressure is lower than in MV.

8.2 Consolidated viewpoints of the relevant industry associations

In addition to conducting individual interviews, we spoke with interest groups and evaluated recent position papers to compile consolidated viewpoints from within the sector. The following bodies and associations are particularly relevant:

- Working Group SF_6 (AK SF_6), central cross-association body in Germany (ZVEI, FNN, BDEW, VIK), representing manufacturers and users;
- Association of Electrical Engineering and Electronics Industry (ZVEI), representing manufacturers;
- Forum network technology/network operation in VDE (FNN), representing, in particular, grid operators as a user group;
- European Association of the Electricity Transmission and Distribution Equipment and Services Industry (T&D Europe), representing European national associations e.g. ZVEI.

The table below gives an overview of the relevant opinions, publications and viewpoints of these bodies and associations. In general, the consolidated overall picture of the associations reveals strong reservations concerning the usability of alternative technologies. This is particularly evident in the clear position that alternative solutions are currently still in the research stage. In the conducted interviews, experts (manufacturers and users) and representatives of international organisation like T&D Europe or Institute of Electrical and Electronics Engineers (IEEE, Alternative Gases Task Force) expressed fewer reservations. For instance, individually, they referred to the possible uses of alternative technologies for specific usage scenarios in MV and HV.

Table 26: Overview of relevant viewpoints, publications and opinions by groups and associations interviewed

Source: Own research

Group, Association	Central viewpoints	Publications, Opinions
Working Group AK SF_6	• SF_6 is centrally important for supply security. • Ecologically balancing SF_6 is critical; SF_6 emissions are still minor as a percentage of total emissions • Toxicity of SF_6 switching- and decomposition products are critical • Alternative solutions are currently in research stage • Extensive tests and experience with long-term stability are still required • Central criteria for evaluating alternatives: Overall cost balance and ecological balance • Uniform solution necessary for all sectors	• Voluntary self-commitment of the industry (2005) [SOLVAY et al., 2005] • Clarifications for F-gas regulation (EU) 517/2014 (2015) [EU, 2014] • Opinion in the scope of survey through project consortium (2016)
ZVEI	• The replacement of switchgear and switching devices from the first-generation and, if necessary, the second-generation with devices of the latest generation presents a significant potential to reduce SF_6 emissions • Target-oriented incentive schemes could empower and encourage the introduction of SF_6-free alternatives. • The use of SF_6 must continue to be allowed beyond the year 2030. • The total amount of emissions permitted can be halved by 2030 in accordance with the voluntary commitment (17 t p.a. by 2020).	• Roadmap to reduce SF_6 emissions from switchgear and equipment [ZVEI, 2017]

Group, Association	Central viewpoints	Publications, Opinions
FNN	• SF_6 is a proven insulation and arc-quenching gas; it is highly reliable and economical • ONE gas or gas mixture, which is equivalent in all applications to SF_6, is currently not available despite scientific research. However, there are alternatives for individual applications; for example, insulating gas in medium-voltage. • Alternatives must fulfil similar requirements: service life, reliability, availability, environmental properties, economic feasibility	• Position paper by users on alternatives for the use of SF_6 (2016) [Bohn, 2016]
T&D Europe	• SF_6-free technologies exist for specific applications • The industry aspires towards constant emission reductions in SF_6 installations and research of alternative solutions • For each alternative technology, extensive testing is necessary before market launch • Development and agreement on uniform evaluation criteria necessary	• Technical manual for evaluation of alternative gases (2016) [T&D Europe, 2015b] • Position paper on SF_6 and alternatives (2016) [T&D Europe, 2015a] • Further reports on technical status of SF_6 alternatives and regulatory framework conditions are currently under preparation, to be published 2017-2018

8.3 Overall mood from the technical discussion dated 06/03/2017

The following summary of the technical discussion dated 06/03/2017 summarises essential parts of the discussion and the outcomes from the project team's perspective. The project team makes no claim to exhaustiveness. We do not take into account the market shares of the representative manufacturers but refer instead to majorities among the circle of participants.

First, points discussed in general are described and summarised. In the sections that follow, the outcomes of the three discussion blocks on

- medium voltage,
- high and extra-high voltage and
- non-technical barriers and market acceptance

are explained. In the first step, an overview of the opinions expressed on the individual theses formulated by the project teams is shown in a table. This is followed by the statements and opinions made during the discussion.

8.3.1 General results

Monitoring of emissions and terminology 'switchgear'

- There is no common opinion as to whether and what kind of switching devices or instrument transformers are to be viewed fundamentally as either part of switchgear or separate equipment. This shows that there is a need for a clear and uniform terminology/definition. The Work Group AK SF_6 will take up this problem

Voltage value for the boundary between medium and high voltage

- The group of participants agreed upon the use of the limit of 52kV (rated parameter) based on the IEC standard IEC 62271-200. However, for the classification/discussion of solutions in medium-voltage, the voltage ranges of < 36kV as well as > 36kV up to and including 52kV must be differentiated. In Germany, the equipment is used almost exclusively in the range of up to 36kV.

8.3.2 Block A: MV electrical equipment

Table 27: Summary of opinions on the individual theses (survey results)
Source: Own research

Thesis statement	is correct	is correct with limitations	is relevant
Reduction potentials among SF_6-insulated installations in medium-voltage are very limited.	• Moderate agreement • No rejection	• Low agreement • No rejection	• Moderate agreement • No rejection
Up to 24kV, technically sophisticated alternative technologies are available.	• Low agreement • Low rejection	• Low agreement • No rejection	• Low agreement • No rejection
The current lack of standardised solutions prevents the introduction / of alternatives.	• High agreement • Low rejection	• Low agreement • No rejection	• High agreement • No rejection

Current level and further reduction in the use of SF_6 in SF_6-insulated switchgear

- *Comment of participant / discussion:* For switching devices and switchgear in general, there is general agreement with respect to reduction potentials. In the essential areas of production and operation of current technologies, the development potential for reduction of emission has been exhausted to a large extent in recent years. For modern switchgear, the participants estimate the annual emission rates at far below 0.1% of the fill volume.

- Among 'other electrical equipment' (for medium *and* high voltage), such as bushings or instrument transformers, there is no clear consensus regarding reduction potentials. The discussion revealed a need for clarification with respect to the demarcation of equipment categories and the definitions upon which monitoring is based.

- *Result:* Emission rates are low for modern switchgear using SF_6. For this reason, further potential for reduction under continued use of SF_6 is considered insignificant and would involve very high effort. Further reduction would be possible only with alternative technologies or gases.

- *Result:* Among 'other electrical equipment' (for medium *and* high voltage), there is a need for further discussion on demarcating/defining and possible reduction potential. The discussions are to be continued within Work Group AK SF_6.

Technical availability of alternatives to using SF_6 in switchgear

- *Comment of participant / discussion:* Vacuum is the state-of-the-art technology for circuit-breakers. No consensus was found with respect to the question of whether vacuum is the state-of-the-art technology for load switches. For the majority, arc-quenching media for load switches are not selected on the basis of technical aspects, but on the basis of cost.

- In terms of insulation media, sufficiently similar alternative technologies are available[18] for most applications (incl. air-insulation, insulation with solids). With regard to alternative gases[19], however, certain questions (e.g. environmental compatibility, long-term behaviour) remain unanswered. For specific usage scenarios that require voltage ranges ≥ 36kV or very high rated currents, further technical developments are necessary for the time being.

- *Result:* Even if there is no consensus with respect to the technical availability of alternative technologies, the majority sees no technical limitations for the use of alternatives in a large number of usage scenarios in medium-voltage.

[18] Alternative technologies include all technologies available on the market that do not use SF_6 as the insulation and/or arc-quenching medium.

[19] Alternative gases include all gaseous insulating and arc-quenching media that can be considered for use in switchgear.

Costs[20]

- *Comment of participant / discussion:* At present, the participants assume higher but not prohibitive costs for alternatives.

- There is no consensus regarding the future development or possible reduction of costs. However, the majority assumes that the degree of standardisation and the required specifications will have a decisive influence on the costs. The discussion revealed a need for even further discussion and the insight that, for a clearer understanding of the term *standardisation,* a distinction must be made between international standards and the specific standards demanded by users.

- *Result:* At present, the costs for alternatives are higher but are not considered prohibitive (see also the general supplement in Block B).

8.3.3 Block B: Electrical equipment in high and extra-high voltage: State-of-the-art technology of SF_6 and alternatives

Table 28: Summary of opinions on the individual theses (survey results)
Source: Own research

Thesis statement	is correct	is correct with limitations	is relevant
Only one alternative gas will become prevalent in the long run.	• Moderate agreement • Low rejection	• High agreement • No rejection	• High agreement • No rejection
We need a longer pilot phase that equally considers multiple alternatives. This phase requires a commitment from manufacturers and users.	• High agreement • No rejection	• -	• High agreement • No rejection

Monitoring emissions and reduction potentials in the use of SF_6

- *Comment of participants / discussion:* In HV installations, relevant developments have been seen in recent years/decades with respect to reduction of emission rates. The difference in leakage rates between old and new installations in high-voltage is much higher than in medium-voltage installations. The reason for this is that medium-voltage installations using SF_6 were introduced later than high-voltage installations, so manufacturers could benefit from years of experience. Despite this fundamental classification, the discussion

[20] Manufacturers represented in the Work Group SF_6 largely abstained from commenting on the topic of 'costs'.

revealed that there is no single understanding of the definition of 'old' installations (time reference, technology, etc.). Furthermore, current monitoring processes allow only slightly quantitative/reliable statements for leakage rates (in particular in MV and in case of 'other electrical equipment') and regarding the stock of old installations.

- Referring to the discussion in block A, a differentiated view of further equipment, such as separate switching devices, bushing or instrument transformers, is deemed necessary.

- *Result:* Reduction potentials are seen primarily among old installations. At the same time, there is a need for clarification regarding the demarcation/definition and the valid monitoring/valid recording of the percentage of old installations. Furthermore, there is a need for more discussion with respect to 'other electrical equipment' (see discussion block A).

Technical availability of alternatives for the use of SF_6

- *Comment of participant / discussion:* The participants expressed that it is clearly necessary to gain more knowledge with respect to the characterisation and a comparative evaluation of all alternatives (this applies also to medium-voltage applications).

- The topic of standardisation took on a central importance in the discussion. The participants see a need for further discussion here. At the same time, there were differing opinions as to which areas require standardisation and what this means e.g. comparable technical features or requirements of the customer or a uniform gas.

- *Result:* Many participants avoiding taking a clear position with respect to the different alternative technologies/gases. Diverging opinions are seen here between manufacturers and users. The users showed a desire for directly comparable analyses and a solution in the market that is offered by all manufacturers. In contrast, the manufacturers consider a certain competition as advantageous, because the alternative gases cannot replace the entire usage area of SF_6 1:1.

- Furthermore, a framework should be put in place for introducing different options, since it cannot be foreseen at present which alternative might cover most of the application fields completely.

Costs

- *Comment of participant / discussion:* Generally, the users have very little information about the possible additional costs of alternatives. According to manufacturers, the costs for installations with alternatives in high-voltage are difficult to estimate.

- Some operators emphasise that even moderate additional costs cannot be accepted, even if they were to be recognised under the regulations for public distribution grids. Network charges are a politically sensitive topic. The question of what additional costs are reasonable, therefore, must be examined and discussed separately and appropriately.

- *Result:* The question of reasonable costs must be answered for public networks within the context of incentive regulations and hence within the regulatory framework (this applies to medium *as well as* high voltage applications).

8.3.4 Block C: Questions of market acceptance, non-technical barriers for the introduction of alternatives

Table 29: Summary of opinions on the individual theses (survey results)
Source: Own research

Thesis statement	is correct	is correct with limitations	is relevant
The industry representatives see a variety of possible instruments. There is no consensus in terms of prioritising policy instruments, but there is a preference among individual participants for support instruments.	• High agreement • No rejection	• -	• High agreement • No rejection
Additional costs related to investments and operating costs are also relevant in the regulated market.	• High agreement • No rejection	• -	• High agreement • No rejection
The challenge is not one alternative gas, but a variety of alternative gases.	• High agreement • No rejection	• -	• High agreement • No rejection

Uncertainty about the future regulatory and policy framework (What kind of regulatory framework do you need as a manufacturer/user?)

- *Comment of participant / discussion:* Different types of instruments were discussed. Market incentive programmes, in-house incentive programmes or bans/taxes.

- Regarding the support of alternatives, challenges are seen in terms of financing and the question of where the support models should be applied. For instance: Should only new alternatives be supported? This would be disadvantageous to alternatives that already exist. Should the focus be on the research programmes (e.g. environmental compatibility)?

- Examples of in-house incentive programmes among operators were mentioned for the Netherlands and Switzerland (financial penalties for SF_6, environmental funds). However, these are based on voluntary implementation by individual companies.

- The incentive effect of a tax on SF_6 is viewed with scepticism because SF_6 accounts for a low percentage of the total cost of an installation.

- Different opinions were expressed during the discussion on the subject of possible bans. Few participants endorsed bans, while others clearly opposed them.

- *Result:* There is a consensus that a reliably planned regulatory framework is necessary. There is no clear opinion or demand from the sector with respect how the framework is designed. Some of the participants expressed a preference for support instruments.

Investments and operating costs (user-side)

- *Comment of participant / discussion:* In the discussion, participants took a nuanced view based on voltage levels and regulated/non-regulated markets.

- Currently, there are factually no operating costs in medium-voltage. In the high-voltage, operating costs are incurred that were assumed by one participant to be comparable to the costs of alternatives.

- Within the regulated field (public supply grids), reasonable additional costs in investment depend on the regulatory framework. In the non-regulated field, additional costs are not necessarily considered prohibitive. However, decisions are made in the non-regulated market with regard to price that can lead to the exclusion of an alternative in the event of price differences.

- During the course of the discussion, it became evident that the users have little information about possible additional costs for alternatives.

Complexity of processes and handing of alternative gases

- *Comment of participant / discussion:* Currently, users deploy various technologies from different manufacturers. This results in differences in terms of equipment handling (but not in terms of gas handling). However, multiple/different gases would increase the variety.

- *Result:* Generally, the use of a limited number of different gases is considered possible, but the participants envision challenges regarding staff training and work safety as well as the performance and storage of gas-handling devices, measurement instruments and replacement parts.

9 Instruments and Measures for SF_6-free Transmission and Distribution of Electrical Energy

The goal of this project is to identify and rank technological alternatives and specific courses of action for replacing or reducing the use of SF_6 in newly constructed electrical equipment. In the preceding chapters, we have described technological possibilities for achieving this goal. To come even closer to the goal of reducing the usage of SF_6, we will now address possible instruments and measures. The discussion will focus on two questions:

- Which instruments [21] and measures are potentially suitable?
- How can these possible courses of action be evaluated in comparison to one another?

The following sections will provide a systematic overview and evaluation of possible courses of action[22].

Policy instruments are intended to influence the decisions and actions of actors in a society, and to bring about changes in everyday practice. Preconditions for effectively designing such change processes are the existence of alternatives to the status quo, and knowledge of these alternatives among stakeholders. The first part of the report is explicitly devoted to this aspect: it identifies for which electrical equipment in which areas of application and at which voltage levels alternatives to the use of SF_6 generally exist. It also clarifies for which applications such alternatives are currently unavailable. In these instances, the use of policy instructions which aim to replace SF_6 accordingly show little promise of success, and are therefore not very constructive.

Below, we take the view that the existing, general framework conditions are a given fact. During the discussion, we will highlight which options are implementable on the national level, and which require a European or an international approach. A further important aspect is the degree to which instruments tie in with pre-existing regulations. Conversely, it is important when introducing new courses of action to identify any possibly conflicting regulations, and to assess their significance.

The research contains numerous different classifications of environmental policy instruments. It is conventional to distinguish between three classes (cf. e.g. [Jänicke et al., 2003; Jacob et al., 2016]): informative, economic and normative instruments. These classifications are also used below in this report:

- **Informative instruments** include information campaigns, industrial forums or conferences devoted to discussing pros and cons of SF_6, as well as alternatives and limitations on its usage (e.g. the GIS User Forum at TU Darmstadt, CIGRE work groups, as well as associations).

[21] Policy instruments are defined as ‘specific measures carried out by various environmental policy-makers to influence processes in accordance with environmental policy objectives’. [Pollert et al., 2016] In the literature, the terms ‘policy measures’ and ‘policy instruments’ are often used synonymously. As such, we will also use these terms synonymously in this report.

[22] In the statement of work for this project, these possible courses of action are paraphrased into strategies.

- **Economic instruments** provide financial incentives for reaching goals. On the one hand, these may be monetary rewards which stimulate SF_6 alternatives (e.g. in the form of subsidies). In other cases, undesirable practices may also be sanctioned; e.g. to raise the costs of using SF_6 through taxation or imposing fees, thereby creating incentives to change such practices.

- **Normative instruments** refer to rules and bans, the intention of which is to allow (environmental) policy goals to be reached. These can also be referred to simply as 'standards'. The main features of the current voluntary commitments can also be seen as normative measures.

Additionally, it is important in this context to categorise the instruments according to the **target groups** to which they apply. These particularly include:

- **Manufacturers** of electrical equipment: during the product design process and creation of their product portfolios, manufacturers wield decisive influence over the future use of SF_6.
- **Users** considerably influence the volumes installed through their decision-making and prioritisation of selection criteria when making purchases. Indirectly, procurement practices influence product development and the design of production processes among manufacturers[23]. In terms of operation, user behaviour is decisive for actual emission levels.

The various instruments do not necessarily have to be enacted and enforced by environmental policy-makers. We also include voluntary measures (e.g. sectoral agreements) among manufacturers and/or users in the categorisation we use in the analysis.

At this point, it is appropriate to repeat a limitation that applies to the entire consultancy project: the scope of these studies extends only to new installations. Consequently, instruments that are suited to achieving emissions reductions in existing equipment and installations are not studied in depth. Industry representatives have, however, emphasised during various interviews that there are significant and easily achievable potentials for reducing SF_6 emissions in existing equipment and installations; e.g., through replacing old installations. Therefore, such courses of action were included for informational purposes during the creation and evaluation of the concepts (see section 9.2.5). At the same time, we make no attempt to provide an exhaustive analysis.

[23] Manufacturers describe how product tests are still carried out with SF_6 based on customer requirements, although, from the manufacturer's perspective, alternative gases also exist which would meet the requirements.

9.1 Systematisation and Evaluation of the defined Instruments and Measures

Based on the aforementioned categorisation, relevant instruments and measures have been identified for the context of SF_6 emissions. In the discussion, attention is devoted to the following criteria:

- **Effectiveness:** Is the measure effective in reducing SF_6 emissions?
- **Efficiency:** Which measure produces the greatest reduction is SF_6 emissions for the lowest cost/least amount of effort? (A measure that is ineffective can therefore also not be efficient.)
- **Feasibility:** Can the measures be implemented successfully, and can the implementation be verified? To what extent will measures be accepted by the stakeholders involved (industry players)?
- **Distribution Effects:** Will the measure result in an appropriate distribution of costs and benefits among the stakeholders involved?

Table 30: provides an overview of all instruments and measures that have been identified. It also gives a general assessment of the measures in terms of the criteria listed. Caution and care should be used when interpreting these findings, because each evaluation depends greatly on the specific configuration and level of development that has been achieved. The subsequent sections contain a detailed description of relevant measures, including their pros and cons.

Table 30: Evaluation of Identified Measures in Terms of Effectiveness, Efficiency, Feasibility and Distribution Effects. For some groups of instruments, no conclusive evaluation is possible, because the effectiveness, efficiency, feasibility and distribution effects depend heavily on how the individual instrument is designed.
Source: Own research

Category	Measure	Evaluation Criterion			
		Effectiveness	Efficiency	Feasibility	Distribution Effects
Informative	Information campaigns, industry forums, conferences	o	o	+	o
	Product labelling	o	o	+	o
	Monitoring	+	o	o	+
	Introduction of an SF_6 register	+	+	o	o
Economic	Subsidies and support of research and pilot projects	/		+	+
	Taxation, levies, deposits, tariffs	/	+	/	+
	Emissions trading	o … +	+	+	o … +
Normative	Rules and bans (e.g. reduction requirements, caps, incentive regulations, technology-neutral tendering)	/			
	Voluntary commitment	o … +	o … +	+	+
Legend	- Negative evaluation o Neutral evaluation + Positive evaluation / Dependent upon individual configuration; no universal evaluation possible				

With any restrictive measure targeting the production of SF_6-containing installations, there is an inherent risk that production capacities will migrate. The manufacturer's competitive position is at least impaired by restrictions whenever limits are imposed on production in the EU but not on imports. This applies to economic as well as normative measures. Such approaches would, of course, be largely ineffective and characterised by strongly negative side effects. Therefore, with restrictive measures, it is advisable to use great care when designing the instruments and selecting their geographic scope.

9.1.1 Informative Measures

The advantage of informative measures is that they are met with a very high level of acceptance. By exchanging best practices in SF_6-emissions reduction in production, and through comprehensively raising awareness of existing possibilities, alternatives can be opened to less-informed producers, grid operators and public utility companies. In any case, sharing as well as accepting and applying the information is not mandatory, and cannot be required of stakeholders. Ultimately, informative measures achieve only modest effects in highly developed markets where a good flow of information already exists. In Germany, there is already widespread knowledge of the current state of technologies and processes for producing and using electrical equipment with SF_6 as well as its alternatives. Therefore, informative measures here should be seen as complementary measures. There are strong, untapped potentials, particularly in the following areas:

- **Advanced Monitoring of Voluntary Commitments:** During our analysis, we have determined that there are potentials for improving the depth of information in various aspects of monitoring (see 9.2.4 for more details).
- **'Other Electrical Equipment':** During the analysis, it became clear that the topic of 'other equipment' has so far not been discussed in professional circles in proportion to the relevance of its emissions. Accordingly, this topic has failed to secure a prominent position, either on corporate research agendas or in policy debates. Furthermore, there are differences and overlaps in terminologies and definitions in monitoring - in the German domestic context, but, above all, in the European context. In Germany, this group is included in manufacturer monitoring (manufacturing emissions of 'other electrical equipment', compiled by the German Electrical and Electronic Manufacturers' Association/ZVEI) of MV+HV instrument transformers, GIL and transformers. In user monitoring (existing emissions of 'other electrical equipment', compiled by FNN), however, this group only includes HV converters, GIL and transformers. In other European countries, 'other electrical equipment' are not subject to separate reporting. We recommend standardising definitions on the German as well as European levels, and opening up an ongoing discussion of the relevance of this group of electrical equipment. As a result, possible 'quick win' potentials can be gained through the use of alternatives, or research of lower-emission production of 'other electrical equipment' can be intensified in the medium term.
- **Further Guidance and Monitoring of New Products[24]:** Because the field of SF_6 alternatives is currently undergoing non-stop further development, and the discussion of new products is by no means conclusive, we recommend further independent guidance and public classification of new products (e.g. life-cycle assessments conducted by independent institutions to compare alternatives to each other and/or to modern SF_6 switchgear). Targeted replacement efforts, in particular among users, can lead to a reduction in the current barriers (e.g. technology-restrictive tendering) and thus, at least, create an even competitive field for providers of alternative solutions. Regular discussions within professional circles and at public workshops (e.g. Darmstadt) will continue to be beneficial, yet do not need to be explicitly supported.
- **Product Labelling:** It is also possible to indicate the environmental impact of switchgear and 'other electrical equipment' using a product label.

[24] These include chemical substitutes for SF_6, alternative non-chemical solutions and improved SF_6 products, all of which aim to reduce SF_6 volumes.

Options for implementation include, on the one hand, using product labels to emphasise products that are particularly environmentally friendly (for example, the '*Blue Angel*' label), but also include warnings on products with above-average emissions (in production and/or use), as well as, ultimately, an indication of gradual differences (for example, energy-efficiency ratings for buildings). The issuing of such product labels would need to be coordinated by a neutral institution.

At the moment, we see **no need for action on the part of policy-makers with regard to informative measures**. Possible potentials can be tapped by industry representatives and associations. Decision-making authority with regard to product labels would have to be allocated to a neutral institution.

9.1.2 Economic Measures

Economic policy instruments provide financial incentives for reaching goals. These incentives can be targeted at properly reflecting external societal costs which are not represented by the markets. Such costs are often difficult to estimate. As a result, the specification of incentives is often done on a pragmatic basis. In such cases, the expected effectiveness is the essential criterion for calculation.

On the one hand, economic incentives can be achieved through rewards (premiums) that stimulate SF_6 alternatives (e.g. through subsidisation). On the other hand, undesirable practices can be subjected to sanctions (deterrents) which, for example, increase the costs of using SF_6 compared with existing alternatives.

Rewards are granted selectively at early stages of product development. They are intended to stimulate desirable developments. They are also suitable for supporting manufacturers at the market-launch stage, thus ensuring that various, competing alternatives can be tested side by side for sufficient lengths of time. Only in this way are stakeholders able to make informed, balanced decisions with regard to favourable lines of development. Deterrents are applied as corrective measures in mature markets to suppress undesirable practices. They target the effects of products distributed in the context of commercial business models (cf. Figure 25:).

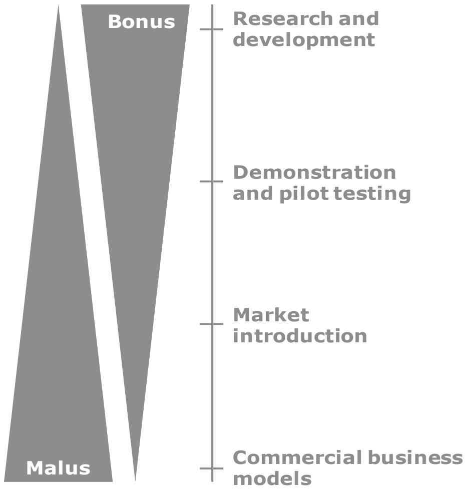

Figure 25: Intensity of Economic Measures by Product Cycle.
Source: Own research.

Incentives are met with a relatively high level of acceptance. However, their implementation results in costs to society at large, which has a significantly negative effect on their cause-effect proportionality. Furthermore, they carry a risk of market distortion (depending on how they are designed and the market proximity of the supported products and projects). In terms of execution, manufacturers can be directly supported, on the one hand, by supporting research into alternatives, greater levels of containment or lower SF_6-emissions production processes. On the other hand, tendering and supporting joint pilot projects and demonstrations could also be conceivable methods of supporting manufacturers and users. For grid operators, it is conceivable to grant recognition for the extra costs of products with lower SF_6 emissions, or for commercial products in the q component of network charge regulation. In such cases, it must be clearly defined in advance which products will receive support status, and how this is to be carried out. This will also require intensive research into how the interpretation of stimulus efforts will impact the environment. Support should be based not on the absolute value of added costs for the electrical equipment, but on the environmental potential.

Taxation, levies, deposits and tariffs are possible forms of fees/financial deterrents. The following list describes some of the possible examples for how these instruments can be designed:

- **Taxation:** The German Federal Government levies a tax on the sale of SF_6 or electrical equipment containing SF_6. Because the collected taxes flow into the government's budget, the deterrent effect is modest aside from increasing the costs of SF_6-related products.
- **Levies:** Buyers of SF_6 and/or electrical equipment containing SF_6 pay a levy that is applied directly or indirectly to stimulate the development of SF_6-free installations or measures for reducing emissions (such as promoting research, a market incentive programme, or recycling facilities). This results in a clear and relatively easy-to-influence deterrent effect. The revenue stream steers clear of the government budget.
- **Deposits:** A deposit is paid along with purchase of SF_6 or electrical equipment containing SF_6. This is refunded in proportion to the volume of SF_6 that is recycled at the end of the product's life cycle.

This does not involve any direct influence over SF_6 usage. Essentially, it is intended to promote a high level of recovery and, if possible, recycling.

- **Tariffs:** Fees are imposed on the import of SF_6 installations with emissions above the industry-standard limit. This enables influence over the competitive position of domestic products versus imports. As such, tariffs only contribute to achieving the goal when combined with other instruments.

Because they work in proportion to SF_6 usage, economic instruments are discrimination-free, at least in this respect. However, the frequent lack of acceptance among target groups and complicated implementation present disadvantages. A particular obstacle is the cost of the bureaucracy that must be set up in order to administer and monitor the fees. Furthermore, it is difficult to determine the correct configuration of fees at the optimal amount. If the amounts of the fees are not set carefully, they can remain ineffective because they are negligible compared with the development of market prices. This is particularly true of SF_6, because the sheer material costs for the gas in relation to the overall costs of the electrical equipment itself are very low. Fees can also have a disruptive effect on the market and/or result in negative effects on the economy in general. Table 31: shows the fundamental pros and cons of various types of fees.

Table 31: Table Possible Forms of Fees along with Pros and Cons
Source: Own research.

Form of instrument	Pros	Cons
Taxation	Potentially discrimination-free with regard to SF_6; relatively easy implementation	Problem of configuring and determining the amount; bureaucracy; limited deterrent effect
Levies	Potentially discrimination-free with regard to SF_6; funds can be used directly for improvements; distribution effects are critical	Problem of configuring and determining the amount; bureaucracy; necessary to create new institutions
Deposits	Improvements and unexpected events during the complete lifetime can be accounted for	Complex bureaucracy and lengthy data storage for all installations built in Germany; long lead time implies major uncertainties (policy framework, value development of the deposit)
Tariffs	Protect the European economy	Possible restrictions under competition law; no incentive for European companies; prosecution is cost-intensive

Beyond the general pros and cons of various forms of fees, certain design decisions can have consequences on the effect of the instruments. Particularly important are the chosen basis for calculation, as well as the choice of who is responsible for paying.

The basis for calculation can be the volume of SF_6 used in each case, the cumulative installed GWP value, or the emissions (SF_6 or CO_2 equivalent) throughout the entire lifetime. It is also possible to calculate using a weighting factor that accounts for various criteria. An advantage to solutions that use GWP or weighting factors is that it is up to the industry to identify and establish suitable solutions. However, an SF_6 metric is easier to implement and monitor. The evaluation table (Table 32:) shows the pros and cons of various calculation bases.

Table 32: Evaluating Pros and Cons of Types of Fees regarding the Calculation Basis
Source: Own research.

Calculation basis	Pros	Cons
Absolute SF_6 volume	Relatively easy/direct implementation possible	Does not account for GWP of alternative gases; does not account for further environmental impact (e.g. toxicity),
GWP (CO_2-e footprint of the installation and/or gas volume)	Other gases can also be accounted for; open-ended design possibilities	The evaluation and implementation are somewhat more complex, because the ratio of SF_6 to GWP is variable
Weighting factor	Can also account for other environmental impacts (e.g. toxicity)	Difficult to reach an agreement on how to determine weighting factors. Complex evaluation and implementation, because a lot of information and complex calculation is required; possibly prone to errors (false assumptions)

At this point, the difficulties of establishing appropriate economic incentives become clear. If the GWP of SF_6 is used as the calculation basis, it is reasonable to orient the monetary value towards the price of CO_2. This is not to say that this method adequately reflects the external costs of greenhouse emissions. However, it clearly represents a broadly accepted benchmark for climate impacts. In a medium-voltage switchgear that contains a fewkg of SF_6, the extra costs of the inert gas used in the entire installation would amount to a few hundred euros, based on today's CO_2 prices. This is a relevant increase in costs. Whether it is sufficient to change the market share of various solutions is, however, difficult to predict. If emissions were to be used as the benchmark, the extra costs would be negligible. To ensure a deterrent effect, the GWP of SF_6 would therefore need to be rated significantly more highly than that of CO_2. Such an approach cannot be expected to meet widespread acceptance within the industry.

As for determining who is responsible for paying, a choice can be made between manufacturers and users. On the one hand, the manufacture can be charged. Such an obligation would, however, need to be imposed at least throughout all of Europe. After all, it is safe to assume that production capacities can be migrated overseas.

The other option is to charge the user. Considering the limited volume of the replacement markets in Germany, such an arrangement might not result in any changes on the part of manufacturers, and would therefore serve only to drive up costs. Such an obligation would, therefore, also need to be imposed at least on the European level. Furthermore, this would not lead to any incentive for manufacturers to reduce emissions in the production process. provides an overview of the pros and cons of placing the responsibility to pay with either manufacturers or users Table 33:.

Table 33: Evaluating Pros and Cons of Making Manufacturers or Users Responsible for Payment

Source: Own research

Party responsible for payment	Pros	Cons
Gas manufacturer/supplier	Up to now, relatively free of obligations	Complex implementation; inevitably goes further than just electrical equipment
Manufacturers (Fees on SF_6 volume from procurement to recycling)	Accounts for all emissions throughout entire lifetime; open-ended design possibilities	Complex in implementation; possible migration of SF_6-intensive production overseas (outside the EU)
Users (Fees on SF_6 volume in purchased products and/or yearly emission rate)	Possible variable weighting for specific kinds of usage and product types	Complex in implementation; probably very ineffective if implemented only on the national level; no incentive to reduce emissions in the production process or disposal

9.1.3 Normative Measures

Normative measures can be either rules (obligations to perform in a certain way) or bans (obligations to avoid certain practices). These can also be referred to simply as obligations or standards. Such standards are intended to achieve specific (environmental) policy objectives. The subjects of such regulations (e.g. manufacturers and users of electrical equipment) must comply with the standard. By causing a change in behaviour, regulations have an effect on the environment in relation to their intended objectives. At the same time, manufacturers and users may incur adoption costs as a result of changing their behaviours, and these costs may vary from one stakeholder to the next. To ensure the effectiveness of normative instruments, deviations from the norm or failure to achieve objectives must be sanctioned. In turn, this requires that such deviations be reliably detected.

An advantage of normative measures is their relatively simple implementation. They result in hardly any direct costs for governmental budgets. At the same time, when implemented successfully, they promise a high degree of effectiveness. Monitoring and sanctioning, however, may result in heavy organisational and administrative workloads, along with high follow-up costs. In the case examined, this is particularly true, because alternatives exist only for specific voltages and uses, but not for others. Consequently, rules or bans must be versatile in terms of their specifications and scope, and must be continually adjusted to remain in line with advances in development. Lastly, strict normative measures lead to acceptance problems due to the high adoption costs imposed on the industry.

With regard to SF_6, bans generally consist of prohibitions or restrictive regulations either on the use or on the circulation of products. Restrictive regulations include obligations to reduce SF_6 for selected uses (for example, through caps and/or phase-downs). Table 34: summarises the essential pros and cons of these options.

Table 34: Pros and Cons of Various Forms of Bans and Restrictions

Source: Own research

Form of instrument	Pros	Cons
Circulation bans on SF_6	Strong, direct effect on the environment; particularly effective in combination with usage bans	Adoption costs very high for the economy; In some cases, alternatives are not yet ready for the market/have not been adequately tested; Possibility that the industry will migrate
Usage bans (production)	Strong, direct effect on the environment in the emissions-intensive production phase; Particularly effective in combination with circulation bans	Adoption costs very high for the economy; In some cases, alternatives are not yet ready for the market/have not been adequately tested; Possibility that the industry will migrate
Caps	Focus on adjustments that can be implemented quickly, effectively and cost-efficiently	Choice of caps is complex/random; Potential for reduction is not fully exploited; Complex in implementation, monitoring, sanctioning
Phase-downs	Adjusting the industry to continually changing requirements is possible; in the case of limited diversity among stakeholders, they provide adequate time to test alternatives; early signalling	Complex in implementation, monitoring, sanctioning

There are various conceivable approaches to designing reduction obligations. For a cap and/or phase-down, standards can be set with regard to the volumes of SF_6 allowed to be emitted during the production and/or entire lifetime of specific groups of electrical equipment. On the one hand, appropriate standards can be set statically. In such cases, a yearly basis is defined and determined as to how many percentage points in emissions reductions are to be reached by a specific point in time. Another option is a dynamically shifting adjustment based on the 'top runner' principle. Recent examples of phase-downs (gradual reductions) of fluorinated greenhouse gases are the EU F-gas Regulation of 2014 and the Kigali Agreement (2016) under the Montreal Protocol on HFCs. It is also conceivable to implement usage bans which forbid or cap the production of electrical equipment that uses SF_6.

Such regulations actively impact only the manufacturers. Indirectly, however, users are just as intensively affected because they must test and compare alternatives.

When designing normative instruments, the following aspects, among others, must be taken into consideration:

- **Calculation basis: SF_6 volume, SF_6 emissions, CO_2-e, weighting factor for various criteria.** For the predefined reduction volume or residual volume in a cap or phase-down scheme, a choice can be made to use either the SF_6 volume or CO_2-e as the calculation basis. As shown above (see Table 32:), there are pros and cons to each scenario. In comparable processes (e.g. phase-down of HFCs), GWP is often chosen as the calculation basis for systematic reasons. With regard to SF_6, using GWP to control a cap and/or phase-down would have the advantage of better comparability and the establishment of analogies with other reduction efforts.

- **Areas of Application: Voltage Levels and the Exception of Specific Types of Use and Categories of Electrical Equipment** Considering the inconsistent availability of alternatives, bans, caps and phase-downs require carefully defined areas of application in which substitutions are in fact efficiently possible. In the medium-voltage range, various technologies exist which have been on the market already for several years. In the high- to extra-high-voltage range, substitution is more difficult. It is also possible to formulate exceptions. For example, certain areas of application demand greatly limited system sizes (e.g. the tower base of an offshore wind turbine, pre-existing buildings with limited space requirements) and therefore – at times - SF_6 solutions. As development continues to advance, further areas of application must be gradually added.
- **Process Level: Production, Operation or Entire Life Cycle?** Emissions during production have fundamentally different causes, than emissions during operation. For example, at the explicit demand of end customers, leakage tests are carried out during the production process using SF_6, although a test with alternative gases (e.g. helium) produces equally valid results in this case. Bans on such processes make rapid reductions possible. These could be based on a reversal of the burden of proof. For example, testing with SF_6 is only permitted if the alternative is proven not to offer the necessary reliability.
- **Geographic Effectiveness: European or National Level?** National initiatives are difficult to implement in globalised markets, and are thus hardly effective. Meanwhile, commitment to binding, international agreements takes a long time to achieve, if it is achievable at all. In light of this, a coordinated European approach seems to be a practicable compromise. One advantage can be seen in the obvious link to the current regulatory framework: the F-gas Regulation regulates the circulation and use of SF_6 on the European level. New normative instruments should ideally be anchored in this regulation.

Voluntary Commitment

Voluntary commitments can be seen as a special form of rules or bans. In such cases, entire industries or specific sectors set binding targets for themselves. Suitable measures and paths towards achieving goals are agreed to within the industry. Voluntary commitments often come into existence in anticipation of announced legal regulations, or to make such regulations redundant. In this light, it is possible to interpret them as normative measures.

In Germany (as well as in other EU Member States and in Switzerland), voluntary commitments are already in effect (see Chapter 7.2 of the section of this report on the state of technology). On the one hand, they include reduction obligations; on the other, they involve institutional instruments such as the monitoring of SF_6 emissions for the purpose of gauging success rates (see also section 7.2.1). Codes of conduct (e.g. mandatory use of technology-neutral, function-oriented tendering) can also be introduced in the form of voluntary commitments.

Since their introduction, significant reductions in SF_6 emissions have been achieved on the national level. A coordinated expansion of such voluntary commitments onto the European level would promise a clear increase in effectiveness and efficiency. In discussions, many industry representatives have explicitly advocated the expansion of voluntary commitments to all Member States.

Voluntary commitments are based on a consensus decision. This has various advantages. Acceptance of the agreed objectives is very high among industry representatives. Measures within the sectors can be implemented precisely and pragmatically, in a way that would be hardly feasibly by legislative means.

The effectiveness has been proven by successful emissions reductions in Germany and Switzerland. A voluntary commitment is also cost-effective, compared with obligations that must be implemented by the government. One limitation to voluntary commitments is that, starting at a certain level, their effectiveness detracts from reaching the goal. As demands increase, participants gradually become less willing to carry on voluntarily. Therefore, regular monitoring is required to determine whether a voluntary commitment is still constructive, or whether additional instruments must be imposed by policy-makers in order to make further progress. Another difficulty is presented by the fact that access, transparency and oversight of the information and data prepared and aggregated by the sectors themselves are not satisfactory in some cases. This makes it difficult to conduct comprehensive, independent analyses. However, considering the corporate interests at stake and the financially sensitive nature of the data, this can only be changed to a limited extent.

In light of the progress that has been made and the processes that have been established, we acknowledge the great significance of voluntary commitments within the industry in Germany. Targeted expansion of such instruments promises even further, substantial progress. Such measures are specifically discussed in section 9.2.3.

9.2 Areas of Activity for Reducing the Use and Emissions of SF_6

The previous sections show a wide spectrum of possible measures for reducing the use and emissions of SF_6. At the same time, they show the wide range of possible forms of measures, and how decisive the specific form can be to the effectiveness, efficiency and implementation of the measures.

Based on our comparative analysis of the instruments and measures, as well as interviews with decision-makers in the fields of policy and business, we have identified five main areas[25] of activity. The policy seminar as well as the second workshop with manufacturers and users in Brussels in September 2017 were particularly enlightening.

I. Exploiting Existing Reduction Potentials
II. Creating a Reliable Framework for the Industry
III. Refining Voluntary Commitments
IV. Refining SF_6 Monitoring
V. Considering the Replacement of Old Installations

The questions associated with these topics must be addressed to provide a basis for informed decision-making. It has become clear that no single '*right*' way can be identified. On the contrary, balancing pros and cons is at the heart of policy-based decision-making. Possible courses of action should not be considered in isolation from one another. They are interwoven and build upon each other. For example, we see sophisticated monitoring as a precondition for comprehensive, efficient measures to reduce emissions.

[25] Based on the terminology of the original performance specification, these can also be referred to as 'concepts'.

9.2.1 Exploiting Existing Reduction Potentials

Since the initial implementation of the F-gas Regulation in 2006, the industry is working to reduce its SF_6 emissions in production processes as well as in the utilisation phase in medium- and high-voltage. Emissions reduction has been achieved, particularly though improved manufacturing processes and technologies, growing awareness, education of the workforce, and recycling. Further reduction potentials exist. However, they are more difficult to tap into than in the past, and they continue to depend heavily on the voltage level, use/type of electrical equipment and area of application. Chapter 5.3 of the section of the report on the state of technology shows that the greatest sources of emissions currently lie in the production of 'other electrical equipment' as well as in high voltage (use and production). SF_6-free alternatives available on the market, on the other hand, can be found especially in medium voltage. For 'other equipment', hardly any SF_6-free technologies have been established. Reduction through improved processes must be studied in greater detail in the future.

Through ambitious efforts, it will also be possible in the future to achieve significant reductions in SF6 emissions despite a rising number of installations. In light of the levels reached by switchgear in medium voltage, the remaining reduction potentials lie, however, primarily in other voltage ranges and applications. The greatest emitters as well as the most easily implementable solutions must still be defined more clearly.
Table 35: summarises the specific challenges as well as potentials for each type of equipment, voltage level and utilisation phase.

Table 35: Potential for Reducing the Volume of SF_6 used/SF_6 emissions per Device Type, Voltage Level and Utilisation Phase
Source: Own research

Area of application	Possible SF_6 savings per device type		
	Medium-voltage switchgear	High-voltage switchgear	'Other electrical equipment'
Production	Modest, not a priority if SF_6 continues to be used	Relevant, challenging, if SF_6 continues to be used, few alternatives	Important/detailed studies needed
Use	Modest, not a priority if SF_6 continues to be used	Relevant, challenging, if SF_6 continues to be used, few alternatives	Important/detailed studies needed
Disposal	In need of consideration	Great efforts are already being taken to keep emissions low; few possibilities for improvements when SF_6 is used	Important/detailed studies needed

Special conditions exist in specific areas of application that should be considered when taking stock of possible reduction measures. The most important points are explained below:

- **High Voltage:** In high voltage, only a slight reduction in emissions from operation has been achieved in recent years. New installations already have a very high containment level. Old installations present the greatest potentials for reducing emissions. First- and second-generation installed switchgears contain substantially higher volumes of SF_6 and emit at significantly higher rates than the latest technologies. Therefore, replacing first and second generation high-voltage switchgear could lead to considerable reductions (see also course of action 5 in section 9.2.5);
- **Medium Voltage:** Newly installed medium-voltage switchgear already features very low emissions rates (<0.1% p.a.). These leakage rates can be seen as technical limit values. Therefore, there is minimal potential to reduce emissions while continuing to use SF_6 in MV installations. Such potentials can only be tapped if SF_6-free solutions are used for MV switchgear in the future. Solutions like these have been available for decades for a range of applications. Furthermore, also in MV installations, replacing switchgear equipment represents a possibility for reducing absolute SF_6 emissions. As with HV systems, emissions increase when existing installations are used beyond their specified service life. The reduction potential cannot be reliably quantified based on the model approach of current monitoring.
- **'Other Electrical Equipment':** Due to the relatively very high level of absolute emissions during the production of 'other electrical equipment' (e.g. condensers, measuring transformers), efforts to reduce emissions should be strengthened. The origin of the emissions and the technical feasibility of reducing them must be analysed. Existing reporting does not identify the precise sources of these emissions, nor does it point conclusively to the type of electrical equipment in question.
- **Production Processes (High Voltage):** The production process of high-voltage switchgear has already been greatly optimised. Possibilities for further reduction through improving operational processes must be evaluated. One possibility continues to be the use of alternative gases for testing purposes during the course of manufacturing.
- **Decommissioning and Disposal:** The first major quantities of SF_6-containing electrical equipment are fast approaching the ends of their technical lifetimes. Therefore, decommissioning and disposal will be relevant topics for controlling emissions in the near future. General requirements are in place for the proper recycling of gases at the end of the equipment's lifetime. These are also part of voluntary commitments adopted by the industry. Considering the widely scattered locations of the electrical equipment and the non-registered categorisation of electrical equipment, manufacturers and users, there is no guarantee that all parties will carry out the processes with the necessary care. Organising a voluntary return system could be an option in this regard.

Further, substantial reductions in emissions will ultimately depend on a widespread switch to alternative technologies/gases. For such a switch to take place, challenges for the reliability, safety and environmental soundness of new solutions must be carefully tested and comprehensively evaluated. These ongoing efforts by manufacturers and users can only be expected if the course is clearly set (see sections 9.2.2 and 9.2.3).

9.2.2 Creating a Reliable Framework for the Industry

Further reduction in the use of SF_6 brings with it adoption costs and a wide range of uncertainties for the industry. During interviews, representatives from manufacturers and users of electrical equipment emphasised that a reliable, regulatory framework is a precondition for sustainable efforts. The industry needs certainty. Accordingly, experiences with voluntary commitments in Germany and other countries (such as Switzerland) have shown that a far-sighted framework which applies to all participants enables substantive progress to be made.

In this context, a binding objective for further minimisation of SF_6 usage is not the only important aspect. For the industry, a consistent evaluation of the properties of relevant alternatives is at least as important. In this area, there are still many uncertainties. Especially the regulated grid operators have a need for reliable statements on how the extra costs associated with alternatives are to be handled in the incentives scheme. A clear statement from the Economics Ministry and the Federal Network Agency (BNetzA) would greatly assuage the industry's misgivings. Preferably, such clarifications should be made uniformly on the European level.

Also the choice of instruments and measures is important to the industry. It makes a difference in terms of the manufacturers' efforts, whether governments impose economic or normative instruments, or voluntary commitment continues to be the decisive basis for further progress (see the following point).

9.2.3 Developing Voluntary Commitments Further

The highly variable challenges and reduction potentials for each individual case raise the question of how these potentials can best be tapped, and which instruments appear to be most suitable. There are two basic paths:

- **Selective:** On the one hand, selective measures can be developed specifically for certain applications. Suitable instruments can be selected depending on the availability of alternatives. In this regard, bans on various applications in the medium-voltage sector are highly feasible. A focus on the most relevant applications could be guided by policy. However, even within the medium-voltage sector, applications are diverse and some require specific exceptions, at least temporarily. This could result in a complex, fragmented regulatory framework in need of frequent adjustment.
- **Integrated:** The second option involves using policies to impose further targets upon the industry as a whole and/or agreeing to such goals within the framework of an expanded voluntary commitment. Such an integrated approach promises to partially sidestep the diversity and complexities of regulations. Selected applications with significant, viable potentials for SF_6 reduction can be immediately and effectively addressed by the industry without having to impose specific regulatory measures. However, applications that have significant SF_6 reduction potential yet pose greater technical difficulties (such as high-voltage equipment) would probably be addressed more slowly under an industry-wide, integrated approach.

The selective approach requires intensive interventions by lawmakers and other regulatory authorities. An industry-wide, integrated approach could take various forms, including hybrid forms, where necessary. It is up to policy-makers to set the targets. They can use suitable instruments to do so. Normative measures could be conceivable, such as mandatory reductions and phase-downs through quota systems, e.g. regulations resembling the HFC quotas from the EU F-gas Regulation. However, economic models such as emissions trading are also possible.

The implementation of industry-wide targets can then be left to the industry itself; e.g. in the course of ongoing voluntary commitments. As a result, various technologies are addressed at different levels of intensity. In any case, the level and binding force of the set targets are decisive for the success of this approach. However, in addition to the specific emissions targets, we also see aspects that require attention in the further development of voluntary commitments.

- **Efforts to achieve ambitious targets must be shared fairly:** the efforts required to further reduce emissions will naturally increase as emissions decrease. Critics of voluntary commitments therefore claim that, starting at a certain level of emissions (i.e. level of costs), voluntary efforts are no longer sufficient for making further progress. That is particularly damaging to ongoing efforts by individual frontrunners who wish to advance low-SF_6 and SF_6-free technologies without a commercial base already being in place for them. A clear code of conduct, combined with a consistent means of sharing the efforts within the industry, can strengthen security, even in a competitive playing field.
- **Greater efforts must be made to address ‘other electrical equipment’.** As an outcome of the analyses, it has become clear that the area of ‘other electrical equipment’ plays a decisive role in further efforts to reduce the use and emissions of SF_6. This will require the industry to broaden its level of knowledge and develop a bold strategy. To a large extent, this aspect will affect only a small number of manufacturers. Even still, the distribution of efforts within the industry itself will be essential for facing the oncoming challenges.
- **Emissions - Not Emission Rates:** The development of emissions in the field of medium-voltage installations shows that successes in reducing emissions rates are insufficient from an environmental policy perspective. In light of the immense increase in the number of installations, absolute emissions have once again been on the rise recently, despite the fact that emission rates have been cut to the technical minimum. Therefore, it is reasonable to demand that targets be focussed on absolute emissions. In the long term, this will stimulate the introduction of alternatives.
- **Substitution Road Map:** Ideally, the industry will work out a road map for further reduction in the use and emissions of SF_6, as well as the introduction of alternatives. At the same time, interim steps along the way to reaching the goal should be purposefully quantified. This will support in evaluating the progress and increase the possibility of making targeted readjustments whenever difficulties occur, without the need for immediate action on the policy level. With all due reservations, such a road map would also provide an additional degree of certainty to all parties involved.
- **(Voluntary) Commitment by Users to Functional, Technology-Neutral Tendering:** In current practice, tendering documents for new electrical equipment regularly refer ‘out of habit’ to SF_6 installations. A requirement to generally avoid this specification in tendering and, in the future, to tender according to functionality would provide suppliers of alternative solutions with at least an equal competitive position, while also increasing product diversity. Whether such a rule would ensure that buyers evaluate all proposals equally before rewarding a contract is, of course, impossible to guarantee.
- **Decommissioning and Disposal:** Proper recycling, reuse, disposal and destruction of SF_6 from decommissioned electrical equipment is already regulated in general. A detailed agreement on the processes and their oversight seems appropriate, in light of the volumes to be dealt with in the medium term. The

handling of electrical equipment from which the gas currently cannot be recycled without excessive effort (e.g. measuring transducers) should be given particular attention at this time.

- **European Coordination:** An expansion of voluntary commitments to all of Europe would have an explicitly positive influence on the effectiveness of the measures. Mandatory goals set by policy-makers are purposefully pursued on the European level. An incremental standardisation on topics where consensus can be reached is advisable in light of the threat of delayed action otherwise.
- **Supplemental Policy Measures:** As a supplement to voluntary commitments adopted by the industry, specific instruments can be implemented on the policy level. They allow 'low-hanging fruit' to be seized that would otherwise only be attainable with delays. One option would be to impose targeted sanctions on inadequate gas recovery and recycling. These could ensure that the already mandatory use of recycling with the best available technologies is effectively carried out. Effective sanctions must clearly exceed the costs of disposal.

Furthermore, incentives systems can be useful in specific areas. However, these must be applied with moderation due to the risk of market distortion and deadweight effects.

- Supporting the replacement of leaky equipment.
- Supporting the market launch of alternatives by buffering against additional costs and risks.

Should a voluntary commitment fail to meet expectations, deeper-impact policy instruments must be considered. Outlining a concept for the planning, geographic scope and targets of such a 'fallback scenario' would create certainty, even if this scenario is not desirable for anyone involved. The availability of such a concept also increases political credibility and clout. It is part of the certainty that the industry demands (section 9.2.2).

9.2.4 Developing SF_6 Monitoring Further

Functional SF_6 monitoring is a precondition for efficient and effective measures. If effective measures are to be established and carried out by policy-makers or the industry itself, it is necessary to know where emissions are occurring. Current methods and aggregation levels of SF_6 monitoring within the framework of voluntary commitments in the industry do not sufficiently allow for an independent evaluation and comparison of the performance levels achieved, or the identification of specific emissions sources. Important indicators that would allow sound decision-making remain obscured in the cumulative reporting. The necessity for solid, transparent and detailed SF_6 monitoring was repeatedly emphasised during interviews with stakeholders. However, there are many difficulties associated with further improvements in monitoring. Plus, there are mixed opinions with regard to suitable options. Below, we discuss the pros and cons/challenges in improving three areas of monitoring:

- **Emissions oversight and reporting** (bottom-up);
- An **SF_6 register** in the form of a database on current oversight of the quantity, location, age and possibly the emissions rate of individual SF_6 switchgear.
- **Atmospheric emissions measurement** (top-down).

Emissions Oversight and Reporting

The current calculation of the amount of SF_6 in Germany is made using a running inventory based on reporting from manufacturers. Emissions are determined based on an emissions factoring method. Monitoring of SF_6 volumes and emissions is compiled based on projections and aggregated manufacturer data. Because the volumes of gas that occur in each piece of electrical equipment depend heavily on the technology, manufacturer, build year and operating conditions, it is currently impossible to attain a valid assessment of the main emitters based on the aggregated volume data. Furthermore, there is considerable inconsistency in the monitoring systems from one European country to the next. Therefore, it is hardly possible to compare emissions on the European level.

We consider it necessary to adjust the monitoring system in the following respects:

- Make disaggregated data accessible to public authorities: less aggregated data would help authorities to identify the worst emitters and to implement effective, efficient measures based on this, as well as to monitor progress towards reaching targets.
- Standardise reporting systems on the EU level in all relevant respects: the introduction of a coherent European monitoring system would be useful for comparison purposes and necessary in case of future EU-wide measures. However, there are highly inconsistent visions among the various countries when it comes to monitoring. This has already resulted in the decision reached during the latest discussions of implementing an EU-level SF_6 reporting system (in connection with the updated F-gas Regulation in 2014) to concentrate first on national reporting practices alongside the reporting requirements under the F-gas Regulation 517/2014[26]. Industry experts expect that the establishment of an EU-wide methodology will take at least a decade. However, this is no reason not to get started and to push for an incremental harmonisation of reporting practices, as needed.
- Expanding the Responsibilities of Gas Producers and Suppliers: Currently, gas producers do not report on SF_6 volumes. Involving them in reporting would simplify the entire process. The confidentiality and anonymisation of market-relevant data must indeed be given particular consideration, considering the limited number of market players. However, this could be maintained by limiting access to the data. The various import and export streams of European and non-European suppliers would, of course, also need to be depicted adequately. This is an additional argument in favour of a coordinated European approach.
- Eliminate Lack of Clarity Surrounding the Term 'Other Electrical equipment': There are uncertainties regarding the distinctions between categories of electrical equipment, voltage levels and the definitions upon which monitoring is based. These should be eliminated to identify potential options for reduction.

Measurement-based determination of the real emissions of individual switchgear and electrical equipment was encouraged during interviews with industry representatives, but seems inexpedient. Quantitative measurements of emitted gas from existing electrical equipment run into physical and metrological limitations due to the extremely low concentrations (large substations, enclosures with forced ventilation, etc.). Current research results use a combination

[26] SF_6 is covered by the reporting requirements under the F-gas Regulation 517/2014. The data on manufacturing/importing/exporting and applications is, however, not published, because there are too few market participants.

of infrared and electrochemical detection to enable detection of SF_6 by-products well below 0.1%, at least under laboratory conditions [Dong et al., 2017].

SF_6 Register

An SF_6 switchgear register in the form of a database to continually monitor the number, location, age and possibly the emission rate based on maintenance data would facilitate emissions reporting and unify bottom-up and top-down approaches. So far, no SF_6 register exists in Germany.

Such a register could be created for the HV sector without excessive effort. In the medium-voltage sector, the pros and cons would need to be balanced: In the MV sector, the pros and cons would need to be balanced: if only new electrical equipment were to be listed in such a register in the future, the data coverage would remain sparse for many years due to the long lifetimes of the installations. The value of such a database would be very limited. Yet, the number of existing MV switchgear is high. They are extremely spread out and, so far, there are hardly any public or standardised records about their locations, owners or operators. This makes it difficult to register existing installations.

The precondition for data gathering is consensus on collection processes as well as on which data is to be collected and in which format. Such coordination among stakeholders would be a question of years rather than months, even on the national level. Individual companies have already introduced SF_6 registers in the course of their asset management activities, and have tested appropriate methods. Much can be learned from these companies as the discussion of a Germany- or EU-wide register continues. Furthermore, the experiences of EU Member States with regard to refrigerating plant registers can also be used as a reference.

The added value of registering age information, which can be used to create projections of current emissions, is otherwise debatable. The emissions from a switchgear can in fact change throughout the lifetime of the installation. However, age is only one of many factors (environmental conditions, load cycles, materials used for seals, etc.) which influence the condition as well as ageing of the electrical equipment and its components.

Atmospheric Emissions Measurement

We recommend, in addition to existing bottom-up inventorisation activities by industry associations, top-down oversight through atmospheric measurements and reverse modelling. Top-down analyses can supply very specific findings as to the regions and timeframes in which emissions originated. This may help to verify progress achieved in emissions reduction, to refine emissions modelling for the bottom-up inventory and to identify sources in need of attention. Even if some relevant emitters are missing or less reliably registered in the reporting (e.g. soundproof windows, military, non-EU countries), it would be useful to understand the volumes that are not measurable in order to bring top-down and bottom-up analyses closer in line with each other.

Very few studies exist that compare atmospheric emissions with reported figures. Studies from Switzerland and Ireland show strong consistency between top-down measurements and reporting, while one study from the USA reveals significant discrepancies between reporting and emission measurements. In China, only atmospheric measurements exist, while information about reported emissions is unavailable. In other countries, it is expected that the SF_6 emissions monitored by measuring atmospheric emissions do not match with the reported figures. However, this is generally yet to be proven.

9.2.5 Considering the Replacement of Old Installations

The study focusses on new electrical equipment. Nevertheless, because of their relevance in the field, and their relatively high emission rates, old installations deserve particular attention. Industry representatives repeatedly emphasised during expert interviews that a major portion of operational emissions can be reduced in the MV as well as in the HV sector by selectively replacing old installations.

This is backed up by current studies (e.g. [Blackman, 2017; SwissMem, 2017b]) from other countries. If the SF_6 volume is substantially and sustainably reduced in this way, then providing incentives and socialising the costs are justified.

During the process of deciding whether to replace old installations, possible reduction of emissions in operation must be balanced against emissions occurring during the production processes for the new, replacement installations. However, there are no simple, generic and reliable indicators (e.g. the age of the installation) through which the emission level of a specific switchgear can be discerned. Due to the lack of reliable measurements and projections of the total potential, the efficiency and effectiveness of the measures is uncertain and difficult to assess in advance. A clear inventorisation of existing installations, which also serves as a basis for reliably identifying worthwhile installations, is a precondition for implementing such measures. This can only be achieved by the industry itself. Sophisticating monitoring (section 9.2.4) helps.

9.3 Conclusion and Outlook

Ambitious efforts and successes within the German industry have made it possible to substantially reduce SF_6 emissions from electrical equipment in recent years. However, available technological alternatives present fundamental opportunities to continue reducing the use of SF_6. In this regard, we see five areas of activity which include possible instruments and measures for stakeholders. The questions associated with these topics must be addressed to provide a basis for informed decision-making. It has become clear that no single '*right*' way can be identified. On the contrary, balancing pros and cons is at the heart of policy-based decision-making. Possible courses of action should not be considered in isolation from one another. They are interwoven and build upon each other. The five areas of activity defined are:

- **Exploiting Existing Reduction Potentials**
- **Creating a Reliable Framework for the Industry**
- **Developing Voluntary Commitments Further**
- **Developing SF_6 Monitoring Further**
- **Considering the Replacement of Old Installations**

Regardless of the reduction in SF_6 emissions that has already been achieved, there are still potentials for reducing the use of SF_6 in newly installed electrical equipment. The selection of suitable steps is no trivial matter. Applications in which a substitution of SF_6 is technically and financially feasible (medium-voltage switchgear) promise only a limited reduction in emissions. For the essential sources of SF_6 emissions (installations in the high-voltage sector, 'other electrical equipment'), the availability of recognised alternatives is still limited.

Reducing the use of SF_6 requires engagement both from policy-makers as well as from the relevant industries. Mandatory targets must be set by policy-makers. Clear framework conditions for the further application of SF_6, as well as for comparing alternatives with existing products and comparing alternatives with each other, are indispensable. These must also be specified by policy-makers. In terms of implementation, an integrated approach is advisable, which covers the industry as a whole. Ambitious expansion of voluntary commitments within the industry, which has adjusted to the current state of knowledge, appears to be a suitable instrument.

This can be supplemented with specific, focussed measures. At the same time, quota systems similar to the HFC quotas under the EU F-gas Regulation can also be introduced on the European level.

Lastly, a functional reporting system is the basis for effective and efficient implementation of the (legal) framework. To continue making progress in this area, there are many fundamental possibilities for adjustments and improvements.

Political implementability, as well as acceptance of the courses of action that have been developed, are strongly tied to regulation on the European level. National level initiatives are neither promising nor effective. Further formation on potential measures on the European level must be pushed for, although it extends beyond the scope of this project.

The next steps towards successful implementation of the instruments that have been described are the selection and intensive analysis of promising concepts. Especially the impacts of the instruments on business, the industry and the environment must be evaluated based on indicators such as welfare effects, distribution effects, effectiveness, efficiency and acceptance.

10 Appendix

10.1 Thesaurus for the explanation of technical terms (German-English)

10.1.1 General electrical terms

Table 36: General electrical terms for grid levels

Deutsch	English	Explanation
Gleichstrom	Direct Current (DC)	Current, whose direction remains constant in time
Hochspannung (HS)	High voltage (HV)	52kV < rated voltage ≤ 150kV (AC) from grid level perspective; > 52kV from equipment perspective
Höchstspannung (HöS)	Extra-high voltage	> 150kV from grid level perspective
Mittelspannung (MS)	Medium voltage (MV)	1kV < voltage ≤ 52kV (AC)
Niederspannung	Low voltage	voltage < 1kV (AC)
Wechselstrom	Alternating current (AC)	Electric current that reverses its direction at regular intervals.

10.1.2 Technical terms for electrical equipment

Table 37: Technical terms for electrical equipment

Deutsch	English	Explanation
Abgangsfeld	Outgoing feeder	Functional unit is a switchgear normally used to transmit power to the system
Antriebssystem	Actuating system	An actuating system moves the contacts in circuit-breakers between the open and closed switching position. The energy required is normally provided by mechanical spring force. This should enable an automatic opening, subsequent closing and reopening of the circuit-breaker.

Deutsch	English	Explanation
Doppel-Sammelschienen-Schaltanlage	Double busbar switchgear	Switchgear in which the conductors are connected at two busbars.
Druckgasleistungsschalter oder Druckgasschalter	Gas-blast circuit-breaker	Circuit-breaker, in which the switching arc formed after the separation of the contacts is quenched within a few milliseconds by injection of a suitable 'extinguishing gas' (e.g. SF_6)
Durchführung	Bushing	Bushings are components that lead a conductor through a wall (e.g. building wall, grounded enclosure of a transformer) and insulate it electrically.
Einfach-Sammelschienen-Schaltanlage	Single busbar switchgear	Switchgear, in which the conductors are connected at a single busbar.
Erdungsschalter	Grounding switch	The task of an grounding switch is to ground the disconnected installation parts and (in multi-pin grounding switches) to simultaneously short circuit.
Freiluft-Schaltanlage	Outdoor switchgear (and control gear)	Switchgear (see gas-insulated switchgear) for outdoor use, suitable for conditions with wind, rain, snow, frost, icing and heavy dirt deposits. In the high-voltage range, 'outdoor switchgear' is often synonymous with AIS (see air-insulated switchgear). I
Gasisolierte (Übertragungs-) Leitung (GIL)	Gas-insulated (transmission) line	An electrical line that consists of one conductor centred inside a pipe. The pipe contains a compressed insulation gas (usually SF_6 or SF_6 mixtures).
Gasisolierte Schaltanlage (GIS)	gas-insulated switchgear (GIS)	Metal-enclosed switchgear in which the insulation is provided at least partly by a gas other than air at atmospheric pressure. It consists of components like circuit-breakers and disconnecting switches. Unlike air-insulated switchgear (AIS), the gas compartment is secluded from the surrounding air.

Deutsch	English	Explanation
Gasisolierter Transformator (GIT)	Gas-insulated transformer	A transformer that uses SF_6 as insulation gas.
Generator Leistungsschalter	Generator circuit-breaker	Switching devices in high-current connection between generator and machine transformer. The electrical requirements for generator switches are essentially much higher than those for switches in grid use [3], see ANSI 'IEEE' C37 013-1997 regulation.
Geschlossenes Drucksystem	Closed pressure system	Volume that is only refilled at regular intervals by manually connecting an external gas supply e.g. HV GIS (see IEC 62271-203).
Hermetisch abgeschlossenes Drucksystem	Sealed pressure system	Volume for which no further gas supply or vacuum handling is necessary during the expected service life; e.g. pipes of vacuum circuit-breakers, MV GIS.
Hilfsstromkreis	Auxiliary circuit	All circuits in a switchgear near the main circuit (e.g. control circuits).
Innenraum-Schaltanlagen (und Schaltgeräte)	Indoor switchgear (and control gear)	Switchgear for indoor use, in which the installation is protected against environmental influences like, wind, rain, snow, hoar frost, icing and heavy dust deposits (compare to: outdoor switchgear).
Kesselleistungsschalter oder Kesselschalter	Dead tank circuit-breaker	A circuit-breaker in which the interrupter is inside a grounded metallic enclosure. This is exclusively used in HV outdoor installations.
Kontrolliertes Drucksystem	Controlled pressure system	Volume which is refilled independently from an outer or inner gas supply; e.g. compressed air circuit-breaker and compressed air drives.
Lastabwurf	Load shedding	The intentional disconnection of a load in a power supply system due to an abnormal condition, in order to ensure the integrity of the rest of the system.

Deutsch	English	Explanation
Lastschalter	Load switch	Load switches help in switching on and off the equipment and installation parts in an undisturbed state. Unlike circuit-breakers, they cannot interrupt short-circuit currents.
Lasttrennschalter	Load-break switch	A switch that is a combination of a load switch and a disconnecting switch. It fulfils the requirements for a load switch as well as those for a disconnector.
Leckageerkennungssytem	Leak detection system	A calibrated mechanical, electrical or electronic device that detects the leakage of fluorinated greenhouse gases and warns the operator in such a case.
Leistungsschalter	Circuit-breaker	Mechanical switching devices that open and close the circuits (operating and fault currents) under load and can conduct the rated current in the switched-on state.
Luftisolierte Schaltanlage (AIS)	Air-insulated switchgear (AIS)	Switchgear in which the conducting parts are exposed directly to the surrounding air. In HV applications, AIS are located in open air (usually outdoors). In MV, the components of the AIS are covered by a grounded metallic enclosure which is not airtight, but instead only offers protection to persons (see gas-insulated switchgear).
Messwandler	Instrument transformers	Devices for measuring current or voltage. They are used to map currents and voltages to be measured to other current or voltage levels to process them further.
Metallgekapselte Schaltanlage	Metal-enclosed switchgear (and control gear)	Switchgear with a metallic enclosure that is fully grounded.
Metallgeschottete Schaltanlage	Metal-clad switchgear	A category of metal-enclosed switchgear conforming to the ANSI standard. Metal-clad switchgear implies a switching and interrupting unit that can be pulled out. Unlike metal-enclosed installations, the individual functional areas are additionally separated from one another by shields.

Deutsch	English	Explanation
MS Schaltanlage für Primärverteilung	MV switchgear for primary distribution	Switchgear on the medium-voltage side of a transformer station which transforms high to medium voltage. Primary distribution includes switchgear with circuit-breakers, such as in transformer stations from high to medium voltage, but is also used in power plants or main feed lines of large building complexes or infrastructure facilities.
MS Schaltanlage für Sekundärverteilung	MV switchgear for secondary distribution	Switchgear on the medium voltage side of a transformer station which transforms medium to low voltage. The secondary distribution mainly contains switchgear with load switches, supplemented by a switch disconnector/circuit-breaker. This type of switchgear is used in substations of power supply companies and municipalities.
Primärtechnik	Primary technology	Electrical equipment that is directly involved in the transport and distribution of electrical energy.
Ringkabelschaltanlage (RMU)	Ring main unit	An RMU is a completely sealed, gas-insulated, compact switchgear. The rated operating voltage typically has a maximum of 24kV and the rated operating current has a maximum of 630 A. It usually consists of 3 functional units: an incoming cable bay and an outgoing cable bay each with a load-break switch, as well as a transformer bay with a fused load-break (or alternatively a circuit-breaker).
Sammelschiene	Busbar	Low-impedance conductor to which several electrical circuits can be connected at separate points. Usually, the busbar is simply a rail/bar to which the various points of the circuit can be connected.

Deutsch	English	Explanation
Schaltanlage	Switchgear	Typically, a switchgear consists of multiple functional units. Generally, the term refers to switching devices associated with generation, transmission, distribution and transformation of electrical energy, as well as the combination of switching devices with control devices, safety devices, regulating devices, connections, accessories and enclosures. Note: 'Switchgear' in English may refer to both switchgear and switching devices as well as the combination of switchgear and switching devices.
Schaltfeld (Funktionseinheit einer Schaltanlage)	functional unit (of a switchgear installation)	A part of an assembly of switchgear and control gear comprising all the components of the main circuits and auxiliary circuits that contribute to the fulfilment of a single function.
Schaltkammerleistungsschalter oder Schaltkammerschalter	Live tank circuit-breaker	A circuit-breaker in which the interrupter is located inside an enclosure that is insulated to earth. This is exclusively used in HV outdoor installations.
Sekundärtechnik	Control (or secondary) equipment	All auxiliary devices necessary for safe operation of the switchgear. These include the functions of controlling, locking, monitoring, reporting, measuring, counting, registering and protecting.
Sicherung	Fuse	Switching devices that cut off a circuit by melting one or more parts intended for this in the event that currents exceed a specified value.
Spannungswandler	Voltage transformer	Instrument transformers for measuring alternating voltage. They are used to map currents and voltages to be measured to other current or voltage levels to process them further.

Deutsch	English	Explanation
Stromwandler	Current transformer	Instrument transformers for measuring alternating voltage. They are used to map currents and voltages to be measured to other current or voltage levels to process them further.
Transformator	Transformer	A device with two or more windings, which transforms AC voltage into an AC voltage with a higher or lower value by means of electromagnetic induction. In doing so, the frequency remains constant.
Trennschalter	Disconnecting switch	Disconnect switches are meant to disconnect downstream equipment i.e. equipment which is no longer under voltage, from the conducting parts. In this way, they build a visible, reliable separation from the equipment connected downstream. Unlike a circuit-breaker or load-break switch, a disconnecting switch would be destroyed during a disconnect process under load.
Übertragungsnetz	Transmission network	The transmission network transmits electrical energy from generators (power plants) to transformer stations which are closer to consumers.
Umspannwerk, Umspannstation, Ortsnetzstation	Substations (transformer stations, local grid stations)	A part of the electrical energy system at the end of a transmission or distribution network which primarily consists of switchgear and transformers.
Verteilnetz	Distribution network	The distribution network distributes energy from the transmission grid to consumers. Transformer stations are the nodal points in the transmission grid.

10.1.3 Electrical parameters

Table 38: Electrical parameters

Deutsch	English	Explanation
Anstehende Spannung	Applied voltage	Voltage between the connections of a circuit-breaker immediately before switching on the current.
Ausschaltstrom	Breaking capacity	Current for which a switching device is specified in case the current is disconnected.
Bemessungs-Betriebsstrom	Rated normal current	The current for which an equipment is measured.
Bemessungs-Isolationspegel	Rated insulation level	Standardised combination of rated values for the lightning impulse withstand voltage, the switching impulse withstand voltage (where applicable) and the short-term power frequency withstand voltage assigned to a rated voltage.
Bemessungs-Kurzzeit-Stehblitzstoßspannung	Rated short-term impulse withstand voltage	Peak value of the standardised surge voltage wave 1.2/50 µs, which the insulation of a device must withstand.
Bemessungs-Kurzzeit-Stehschaltstoßspannung	Rated switching impulse withstand voltage	Peak value of the unipolar normal surge voltage 250/2500 µs which the insulation of a device with rated voltage of 300kV and higher must withstand.

Deutsch	English	Explanation
Bemessungs-Kurzzeit-Stehwechselspannung	Rated short-term power frequency withstand voltage	Effective value of the sinusoidal alternating voltage in case of operating frequency which the insulation of a device must withstand for a time duration of 1 minute according to the defined testing conditions.
Bemessungs-Kurzzeitstrom	Rated short-time withstand current	Current which a device can conduct during a defined short time in the closed position.
Bemessungs-Spannung	Rated voltage	Voltage value specified by the manufacturer up to which a device is intended for use.
Bemessungswert	Rated value	Current value specified by the manufacturer up to which a device is intended for use.
wiederkehrende Spannung	Recovery voltage	Voltage which occurs immediately after the interruption of the current between the contacts of an open switching device or fuse.

10.1.4 Environmental terms

Table 39: Environmental terms

Deutsch	English	Explanation
Atmosphärische Lebensdauer	atmospheric residence time	Time it takes for a gas in the atmosphere to decompose. The value depends on the decomposition mechanism and is therefore gas-specific.
Treibhauspotential	Global warming potential (GWP)	The global warming potential of a gas is specified in terms of equivalence to 1kg of CO_2. The exact definition of the GWP is listed in the fifth IPCC report.
Strahlungsantrieb	Radiative efficiency	Radiative efficiency is defined as the change in net radiation balance in the tropopause due to a change in the concentration of a greenhouse gas. It is expressed using the unit W/m²/ppb and, together with the atmospheric residence time, determines the GWP of a substance.

10.1.5 Selection of the most important gases and gas mixtures currently discussed

Table 40: The most important gases

Deutsch	English	Trade name	Explanation
Schwefelhexafluorid (SF_6)	Sulphur hexafluoride (SF_6)		GWP = 23,500
Fluorketon C5-PFK	Perfluoroketone C5-PFK	Pure C5-PFK: Novec 5110 Mixed gas in application of ABB (AirPlus): CO_2 and O_2 with C5-PFK;	GWP <= 1
Fluornitril C4-PFN	Perfluoronitril C4-PFN	Pure C4-PFN: Novec 4710 Mixed gas in application of GE (g^3): C4-PFN and CO_2	GWP = 1,490
trockene Luft	dry Air/synthetic air	Mixed gas in application from Siemens (Clean Air): 80% nitrogen /20% oxygen	GWP = 0

10.1.6 Organisations

Table 41: Organisations

Abbreviation	Deutsch	English
ANSI		American National Standards Institute
CIGRE	Internationales Forum für große elektrische Netze	International Council on Large Electric Systems
CIRED	Internationales Forum für elektrischen Energieverteilung	International Council on Electricity Distribution
DIN	Deutsches Institut für Normung	German Institute for Standardization

Abbreviation	Deutsch	English
IEC	Internationale Elektrotechnische Kommission	International Electrotechnical Commission
IEEE	Verband von Ingenieuren aus den Bereichen Elektrotechnik und Informationstechnik	Institute of Electrical and Electronics Engineers
NOAA		National Oceanic and Atmospheric Administration
VDE	Verband der Elektrotechnik Elektronik Informationstechnik (in Deutschland)	Association for Electrical, Electronic and Information Technologies (in Germany)
FNN	Forum Netztechnik/Netzbetrieb im VDE	Forum Network Technology / Network Operation in the VDE
ZVEI	Zentralverband Elektrotechnik- und Elektronikindustrie (in Deutschland)	German Electrical and Electronic Manufacturers' Association
T&D Europe	Zusammenschluss der Fachverbände der Hochspannungsschaltgeräte und Transformatorenhersteller (in Europa)	European Association of the Electricity Transmission and Distribution Equipment and Services Industry
Eurelectric	Union der Elektrizitätswirtschaft (in Europa)	The Union of the Electricity Industry (in Europe)

10.2 Overview of conducted exploratory interviews

Table 42: Overview of conducted interviews

Company	Type
ABB	Manufacturer
Cellpack	Manufacturer
Driescher-Wegberg	Manufacturer
Eaton Electric	Manufacturer
ENERTRAG Energiebau	User - Wind
Evonik	User – Industrial networks
EWZürich	User
GE Grid Solutions	Manufacturer
HSP Hochspannungsgeräte	Manufacturer
Ormazabal	Manufacturer
Ormazabal	Manufacturer
Pfiffner	Manufacturer
RITZ Instrument Transformers	Manufacturer of 'other electrical equipment'
RWE (Westnetz)	User
Schneider Electric	Manufacturer
Siemens	Manufacturer
Solvay	Gas producer
Stromnetz Hamburg	User
Trench Germany GmbH	Manufacturer
Stromnetz Berlin	User
wpd europe GmbH	User - Wind

10.3 Participants in the technical discussion dated 6 March 2017

Table 43: List of participants in the technical discussion dated 6 March 2017

Organisation
3M
50Hertz
ABB
Work group SF_6
Amprion
Avacon / E.on
BMUB
Cellpack
Currenta
DILO GmbH
Driescher Moosburg
Driescher Wegberg
Eaton Electric
Ecofys (3 persons)
ETH Zürich (2 persons)
Evonik
EW Zürich
GE Grid Solutions
Innogy
Netze BW
Ökorecherche
Ormazabal
Pfiffner
RITZ
Schneider Electric
Siemens
Solvay
Stromnetz Berlin
Stromnetz Hamburg
TenneT
TRENCH Group
Umweltbundesamt
Uniper
Forum Netztechnik/Netzbetrieb im VDE
wpd europe
Zentralverband Elektrotechnik- und Elektronikindustrie (in Deutschland)

10.4 Product sheets

Table 44: Product sheets of electrical equipment evaluated in the text Retrieved in October 2016

Manufacturer	Product	Link
ABB	ELK-14C 170kV	http://new.abb.com/high-voltage/gis/pilot-eco-efficient-gas-insulated-switchgear
ABB	ELK-14C 245kV	http://new.abb.com/high-voltage/gis/portfolio/elk-14-c-(up-to-245-kv)
ABB	ELK-04 C 145kV	http://new.abb.com/high-voltage/gis/portfolio/elk-04
ABB	ELK-14 300kV	http://new.abb.com/high-voltage/gis/portfolio/elk-14-(up-to-300-kv)
ABB	ELK-3 C 420kV	http://new.abb.com/high-voltage/gis/portfolio/elk-3-c-(up-to-420-kv)
ABB	ELK-3 550kV	http://new.abb.com/high-voltage/gis/portfolio/elk-3-(up-to-550-kv)
ABB	ELK-4 800kV	http://new.abb.com/high-voltage/gis/portfolio/elk4-(up-to-800-kv)
ABB	ELK-5 1200kV	http://new.abb.com/high-voltage/gis/portfolio/elk-5-(up-to-1200-kv)
ABB	LTA 72D1	http://www02.abb.com/global/gad/gad02181.nsf/0/3b51d425f8c20402c1257a61004db108/$file/High+voltage+CO2+circuit+breaker+type+LTA+-+Enhancing+eco-efficiency.pdf
ABB	LTB D1/B	https://library.e.abb.com/public/9c1ec4b8ebf937f0c1257cc9004b0cda/B.G.%20HV%20LT%20Circuit%20Breakers%20Ed%206en%20LTB%20family.pdf
ABB	LTB D 72.5 – 170kV	http://new.abb.com/high-voltage/AIS/selector/ltb-d
ABB	LTB E	https://library.e.abb.com/public/9c1ec4b8ebf937f0c1257cc9004b0cda/B.G.%20HV%20LT%20Circuit%20Breakers%20Ed%206en%20LTB%20family.pdf
ABB	TG 72.5-800kV	http://new.abb.com/high-voltage/instrument-transformers/current/tg
ABB	IMB 36-800kV	https://library.e.abb.com/public/1b61a98abcb38abec1257b130057b777/Buyers%20Guide%20Outdoor%20Instrument%20Transformers%20Ed%205%20en.pdf
ABB	FOCS-FS 245-800kV	http://new.abb.com/high-voltage/instrument-transformers/current/FOCS-FS
ABB	CPB (capacitor) 72-800kV	https://library.e.abb.com/public/1b61a98abcb38abec1257b130057b777/Buyers%20Guide%20Outdoor%20Instrument%20Transformers%20Ed%205%20en.pdf
ABB	EMF (inductive) 52-170kV	http://new.abb.com/high-voltage/instrument-transformers/voltage/emf
ABB	TVI 72.5-420kV	http://new.abb.com/high-voltage/instrument-transformers/voltage/tvi
ABB	ZX2 Pilot, Oerlikon	http://new.abb.com/docs/librariesprovider27/default-document-library/uw_oerlikon_neu_1hc0114818aa_en.pdf?sfvrsn=2
ABB	ZX2 up to 40kV	http://new.abb.com/medium-voltage/switchgear/gas-insulated-switchgear/iec-gis-primar-distribution/iec-gas-insulated-primary-switchgear-zx2
ABB	ZX0.2 up to 36kV	http://new.abb.com/medium-voltage/switchgear/gas-insulated-switchgear/iec-gis-primar-distribution/iec-gas-insulated-primary-switchgear-zx0-2

Manufacturer	Product	Link
ABB	ZX1.2 up to 40kV	http://new.abb.com/medium-voltage/switchgear/gas-insulated-switchgear/iec-gis-primar-distribution/iec-gas-insulated-primary-switchgear-zx0-2http://new.abb.com/medium-voltage/switchgear/gas-insulated-switchgear/iec-gis-primar-distribution/iec-gas-insulated-primary-switchgear-zx0-2
ABB	ZX1.2: 24kV	https://library.e.abb.com/public/38e230961a85299fc1257d8500327181/DS%202471%20ZX-Family%20en%20A4.pdf
ABB	ZX2: 36kV	http://www.abb.de/product/db0003db004279/c125739900636470c1256ec300510cf9.aspx?productLanguage=ge&country=DE
ABB	ZX2 Airplus: 36kV	https://library.e.abb.com/public/2c5af4103efd4d23a7bf75fa656c0506/DS%202561%20ZX2%20AirPlus%20en.pdf
ABB	ZX2.2: 40kV	https://library.e.abb.com/public/fc6aabb7a6583d64c1257730005c1ab5/ZX2.2%20Brochure%20Rev%20C.pdf
ABB	ZS1: 24kV	http://new.abb.com/medium-voltage/switchgear/air-insulated/iec-and-other-standards/iec-air-insulated-primary-switchgear-unigear-zs1
ABB	UniSec up to 24kV	https://library.e.abb.com/public/60c4ed7ff3104c66b15f0e731795ce8a/BR%20TEC_UNISEC(EN)L_1VFM200002-02%202016.pdf
ABB	Saveplus up to 40kV	http://new.abb.com/medium-voltage/switchgear/gas-insulated-switchgear/iec-gis-rmu-for-secondary-distribution/iec-indoor-gas-insulated-ring-main-units-and-compact-switchgear-type-safering-safeplus
ABB	SaveWind 12-40.5kV	http://new.abb.com/medium-voltage/switchgear/safewind
ABB	SafeRing up to 40kV	http://new.abb.com/medium-voltage/switchgear/gas-insulated-switchgear/iec-gis-rmu-for-secondary-distribution/iec-indoor-gas-insulated-ring-main-units-and-compact-switchgear-type-safering-safeplus
ABB	SafeRing Air up to 12kV	http://new.abb.com/medium-voltage/switchgear/gas-insulated-switchgear/iec-gis-rmu-for-secondary-distribution/iec-gas-insulated-ring-main-unit-safering-air
ABB	SafeRing AirPlus 24kV	http://www.abb.ch/product/db0003db004279/c125739900636470c1256eae0048a62b.aspx
ABB	SafeLink CB 12kV	http://new.abb.com/medium-voltage/switchgear/gas-insulated-switchgear/iec-gis-rmu-for-secondary-distribution/iec-gas-insulated-ring-main-unit-safelink-cb
ABB	SafeLink 12kV	http://new.abb.com/medium-voltage/switchgear/gas-insulated-switchgear/iec-gis-rmu-for-secondary-distribution/iec-gas-insulated-ring-main-unit-safelink-cb
ABB	R-MAG 15-38kV	http://new.abb.com/medium-voltage/apparatus/circuit-breakers/outdoor/ansi-iec-outdoor-vacuum-circuit-breaker-r-mag
ABB	OVB-SDB 15kV	http://new.abb.com/medium-voltage/apparatus/circuit-breakers/outdoor/iec-outdoor-vacuum-circuit-breaker-ovb-sdb
ABB	OVB-VBF Up to 40.5kV	http://new.abb.com/medium-voltage/apparatus/circuit-breakers/outdoor/iec-outdoor-vacuum-circuit-breaker-ovb-vbf
ABB	OHB up to 40.5kV	http://new.abb.com/medium-voltage/apparatus/circuit-breakers/outdoor/iec-outdoor-gas-insulated-(SF_6)-circuit-breaker-ohb
ABB	PVB/PVP-S 12kV	http://new.abb.com/medium-voltage/apparatus/circuit-breakers/outdoor/iec-outdoor-vacuum-circuit-breaker-pvb-pvb-s
ABB	GSec 24kV	http://new.abb.com/medium-voltage/apparatus/isolators-switches-disconnecting switches/indoor-switches/gas-insulated-switches/iec-secondary-gas-switch-disconnecter-gsec
ABB	SFG 24kV	http://new.abb.com/medium-voltage/apparatus/isolators-switches-disconnecting switches/indoor-switches/gas-insulated-switches/iec-indoor-gas-switch-disconnecting switches-sfg

Manufacturer	Product	Link
Eaton	MMS 24kV	http://www.eaton.eu/Europe/Electrical/ProductsServices/PowerDistribution/MediumVoltageSwitchgear/PrimarySwitchgear/MMS/index.htm
Eaton	Power Xpert FMX 24kV	http://www.eaton.eu/Europe/Electrical/ProductsServices/PowerDistribution/MediumVoltageSwitchgear/PrimarySwitchgear/PowerXpertFMX/index.htm
Eaton	Power Xpert UX 24kV	http://www.eaton.eu/Europe/Electrical/ProductsServices/PowerDistribution/MediumVoltageSwitchgear/PrimarySwitchgear/PowerXpertUX/index.htm
Eaton	xGear 24kV	http://www.eaton.eu/Europe/Electrical/ProductsServices/PowerDistribution/MediumVoltageSwitchgear/PrimarySwitchgear/xGear/index.htm
Eaton	Xiria E 24kV	http://www.eaton.eu/Europe/Electrical/ProductsServices/PowerDistribution/MediumVoltageSwitchgear/SecondarySwitchgear/Xiria-E/index.htm
Eaton	SVS 24kV	http://www.eaton.eu/Europe/Electrical/ProductsServices/PowerDistribution/MediumVoltageSwitchgear/SecondarySwitchgear/SVS/index.htm
Eaton	Magnefix 15kV	http://www.eaton.eu/Europe/Electrical/ProductsServices/PowerDistribution/MediumVoltageSwitchgear/RingMainUnits/Magnefix/index.htm
Eaton	Xiria 24kV	http://www.eaton.eu/Europe/Electrical/ProductsServices/PowerDistribution/MediumVoltageSwitchgear/RingMainUnits/Xiria/index.htm
GE	F35 (SF_6)	http://www.gegridsolutions.com/HVMV_Equipment/catalog/f35.htm
GE	F35 (g^3)	http://www.gegridsolutions.com/HVMV_Equipment/catalog/f35.htm
GE	Hams Hall in UK 420kV	http://www.gegridsolutions.com/alstomenergy/grid/Global/CleanGrid/Resources/Documents/Gas%20Insulated%20Lines%20-%20Think%20Grid%20n%C2%B07.pdf
GE	g^3 GIL up to 800kV	https://www.gegridsolutions.com/HVMV_Equipment/catalog/GIL.htm
GE	GL 309 72.5kV	https://www.gegridsolutions.com/alstomenergy/grid/global/Resources/Documents/AIS/AIS/01_Live%20Tank%20CBR_ok/Grid-AIS-L3-GL_309-0097-2015_10-EN.pdf
GE	VL 109 72.5kV	http://www.gegridsolutions.com/alstomenergy/grid/cleangrid/clean-products/products-and-solutions/eco-design/index.html
GE	g^3 current transformer 245kV	https://www.gegridsolutions.com/app/Resources.aspx?prod=SKF&type=1
GE	PABS Air-to-SF_6 245kV	http://www.gegridsolutions.com/alstomenergy/grid/products-services/product-catalogue/electrical-grid-new/electrical-substation-ais/power-transformers/bushings/index.html
GE	PWO 245kV	https://www.gegridsolutions.com/AlstomEnergy/grid/Global/Grid/Resources/Documents/Products/Grid-PTR-L3-Bushings_expertise-0225-2015_10-EN.pdf
GE	SecoGear Metal Clad 17.5kV	https://www.gepowercontrols.com/ex/resources/literature_library/catalogs/medium_voltage/downloads/SecoGear-SecoVac_Catalogue_English_ed09-11_680878-u.pdf
GE	Power/Vac ** Metal Clad 15kV	http://www.geindustrial.com/products/switchgear/powervac-metal-clad-switchgear
Ormazabal	Cpg.1 24kV	http://www.ormazabal.com/en/your-business/products/cpg1-24-kv-iec-2000-315-ka
Ormazabal	Cpg.0 24kV	http://www.ormazabal.com/en/your-business/products/cpg0-24-kv-iec-2500-25-ka
Ormazabal	Gae1250kmax 24kV	http://www.ormazabal.com/de/ihr-gesch%C3%A4ft/produkte/gae1250kmax-24-kv-1250-25-ka
Ormazabal	Amc 17.5kV	http://www2.ormazabal.com/sites/default/files/descargas/CA-505-EN-1303.pdf

Manufacturer	Product	Link
Ormazabal	gae 24kV	http://www.ormazabal.com/de/ihr-gesch%C3%A4ft/produkte/gae-24-kv-630-20-ka
Ormazabal	ea 24kV	http://www2.ormazabal.com/en/nuestras-l%C3%ADneas-de-negocio/air-insulated-cubicles-secondary
Pfiffner	JGF 245 – 550kV	http://www.pfiffner-group.com/fileadmin/files/documents/20_products/JGF_EN.pdf
Schneider Electric	MCset 24kV	http://www.schneider-electric.com/en/product-range/985-mcset-24-kv
Schneider Electric	PIX 24kV	http://www.schneider-electric.com/en/product-range/60678-pix
Schneider Electric	GMA 24kV	http://www.schneider-electric.com/en/product-range/60686-gma
Schneider Electric	SM6-24 (SF_6)	http://www.schneider-electric.com/en/product-range/970-sm6-24
Schneider Electric	SM6-24	http://www.schneider-electric.com/en/product-range/970-sm6-24
Schneider Electric	FBX-E	http://www.schneider-electric.com/id/en/download/results/0/0?aui_3_4_0_1_170=FBX-E&keywordForm=FBX-E
Schneider Electric	Evolis withdrawable	http://www.schneider-electric.com/id/en/download/results/0/0?previousPage=&H1PreviousPage=&orderByCol=&keyword=Evolis+withdrawable&searchAttributeFilter=all&+userAction=true&languageId=0&languageId=1555684&docTypeGroupId=7357956&keywordForm=Evolis+withdrawable&notSearchWithDefaultLangauge=true
Schneider Electric	HVX withdrawable	http://www.schneider-electric.com/id/en/download/results/0/0/Evolis+withdrawable/searchForm?p_auth=t5KfyEIC&_downloadcenter_WAR_downloadcenterRFportlet_docTypeGroupId=7357956
Schneider Electric	SF2 fixed	http://www.schneider-bgclub.com/catalog/2_Aparatura_SrN/3.Aparati_Sredno_naprejenie/Katalozi/SF_circuit%20breakers_EN.pdf
Schneider Electric	Rollarc 12kV	http://download.schneider-electric.com/files?p_Reference=NRJED111211EN-V3&p_EnDocType=Brochure&p_File_Id=3498085192&p_File_Name=NRJED111211EN-web.pdf
Schneider Electric	CBX 12kV	http://download.schneider-electric.com/files?p_Reference=NRJED111211EN-V3&p_EnDocType=Brochure&p_File_Id=3498085192&p_File_Name=NRJED111211EN-web.pdf
Schneider Electric	CVX 12kV	http://download.schneider-electric.com/files?p_Reference=NRJED111211EN-V3&p_EnDocType=Brochure&p_File_Id=3498085192&p_File_Name=NRJED111211EN-web.pdf
Siemens	High-Voltage Circuit Breakers	http://www.energy.siemens.com/br/pool/hq/power-transmission/high-voltage-products/circuit-breaker/Portfolio_en.pdf
Siemens	8DM1	http://www.energy.siemens.com/ru/pool/hq/power-transmission/high-voltage-products/gas-insulated/8dm1/8DM1_Flyer_en.pdf
Siemens	TAG 72.5 – 550kV	http://www.energy.siemens.com/hq/pool/hq/power-transmission/high-voltage-products/high-voltage-products-reliable-products_EN.pdf
Siemens	IOSK 40.5–550kV	http://www.energy.siemens.com/hq/pool/hq/power-transmission/high-voltage-products/high-voltage-products-reliable-products_EN.pdf
Siemens	TVG 72.5-245kV	http://www.trenchgroup.com/Produkte-Loesungen/Messwandler/Induktive-Spannungswandler/SF_6-isolierte-induktive-Spannungswandler

Manufacturer	Product	Link
Siemens	SVS 72.5-800kV	http://www.trenchgroup.com/Produkte-Loesungen/Messwandler/Induktive-Spannungswandler/SF_6-isolierte-induktive-Spannungswandler
Siemens	VEOT/S 72.5-550kV	http://www.trenchgroup.com/Produkte-Loesungen/Messwandler/Induktive-Spannungswandler/Oel-isolierte-induktive-Spannungswandler
Siemens	IVOKT and TMC 72.5 – 300kV	http://www.energy.siemens.com/hq/pool/hq/power-transmission/high-voltage-products/high-voltage-products-reliable-products_EN.pdf
Siemens	SVAS 72.5 – 800kV	http://www.trenchgroup.com/Produkte-Loesungen/Messwandler/Kombinierte-Strom-und-Spannungswandler/SF_6-isolierte-Kombinationswandler
Siemens	AVG 72.5-300kV	http://www.trenchgroup.com/Produkte-Loesungen/Messwandler/Kombinierte-Strom-und-Spannungswandler/SF_6-isolierte-Kombinationswandler
Siemens	SA/SAS Current-T 72.5-800kV	http://www.trenchgroup.com/Produkte-Loesungen/Messwandler/Messwandler-fuer-gas-isolierte-Schaltanlagen/node_763
Siemens	SU/SUD Voltage-T 72.5-800kV	http://www.energy.siemens.com/hq/pool/hq/energy-topics/power%20engineering%20guide/71/06-Products-and-Devices.pdf
Siemens	NXAIR	http://w3.siemens.com/powerdistribution/global/EN/mv/medium-voltage-switchgear/air-primary-distribution-systems/Pages/nxair-family.aspx
Siemens	8BT1 (≤24kV)	http://w3.siemens.com/powerdistribution/global/EN/mv/medium-voltage-switchgear/air-primary-distribution-systems/Pages/8bt1.aspx
Siemens	8BT2 (≥24kV)	http://w3.siemens.com/powerdistribution/global/EN/mv/medium-voltage-switchgear/air-primary-distribution-systems/Pages/8bt2.aspx
Siemens	8DA10	http://w3.siemens.com/powerdistribution/global/EN/mv/medium-voltage-switchgear/gis-primary-distribution-systems/Pages/8da10.aspx
Siemens	NXPIUS C	http://w3.siemens.com/powerdistribution/global/DE/mv/mittelspannungsschaltanlagen/gasisolierte-schaltanlagen-fuer-sekundaere-verteilungsnetze/Seiten/nxplus-c-einfach.aspx
Siemens	NXPIUS 40.5kV	http://w3.siemens.com/powerdistribution/global/EN/mv/medium-voltage-switchgear/gis-primary-distribution-systems/Pages/nxplus-single.aspx
Siemens	NXPLUS C WIND 36kV	http://w3.siemens.com/powerdistribution/global/EN/mv/medium-voltage-switchgear/gis-primary-distribution-systems/Pages/nxplus-c-wind.aspx
Siemens	8DJH	http://w3.siemens.com/powerdistribution/global/DE/mv/mittelspannungsschaltanlagen/gasisolierte-schaltanlagen-fuer-sekundaere-verteilungsnetze/Seiten/8djh.aspx
Siemens	8DJH compact	http://w3.siemens.com/powerdistribution/global/DE/mv/mittelspannungsschaltanlagen/gasisolierte-schaltanlagen-fuer-sekundaere-verteilungsnetze/Seiten/8djhcompact.aspx
Siemens	SIMOSEC	http://w3.siemens.com/powerdistribution/global/DE/mv/mittelspannungsschaltanlagen/luftisolierte-schaltanlagen-fuer-sekundaere-verteilungsnetze/Seiten/luftisolierte-schaltanlage-simosec.aspx
Siemens	3AF0 12 - 40.5kV	http://w3.siemens.com/powerdistribution/global/EN/mv/medium-voltage-outdoor-devices/Pages/life-tank-outdoor-vacuum-circuit-breaker-3af0.aspx
Siemens	SDV6 15 – 38kV	http://w3.siemens.com/powerdistribution/global/EN/mv/medium-voltage-outdoor-devices/Pages/dead-tank-outdoor-circuit-breaker-scv6.aspx
Siemens	3AF04 /3AF05 27.5kV	http://w3.siemens.nl/powerdistribution/nl/nl/mv/medium-voltage-outdoor-devices/Pages/life-tank-outdoor-vacuum-circuit-breakers-3af04-3af05.aspx#

Manufacturer	Product	Link
Siemens	8VN1 Blue GIS 145kV	http://www.energy.siemens.com/hq/en/power-transmission/high-voltage-products/gas-insulated-switchgear/8vn1.htm#content=Technical%20Data
Siemens	8DN8-6 170kV	http://www.energy.siemens.com/hq/de/stromuebertragung/hochspannungsprodukte/gasisolierte-schaltanlagen/8dn8.htm

10.5 Figures of components

Figure 26: Circuit-breaker

Source: [ABB]

Figure 27: Load switch

Source: [ABB]

Figure 28: Disconnecting switch

Source: [ABB]

Figure 29: SF_6 tank with built-in load-break switch, grounding switch and power unit
Source: [ABB]

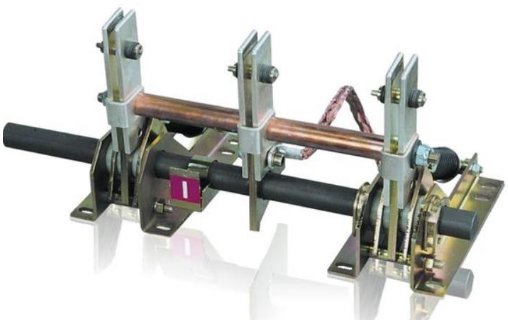

Figure 30: Grounding switch
Source: [ABB]

10.6 LCA: Life-cycle assessment of gas-insulated switchgear

Alongside comparisons of GWPs of insulation gases, life-cycle assessments (LCAs) can be used to evaluate the environmental impacts of gas-insulated electrical equipment. LCAs [[ISO 14040, 2006] help calculate the complete environmental impacts of the equipment throughout its life cycle. To do this, all processes, which cause directly or indirectly effects on the environment (e.g. contribution to greenhouse effect, ozone hole, acid rain, smog formation), must be examined from production till the disposal of an installation. The variables influencing the environmental effects are many and include: Material, current mix, production of raw material, auxiliaries and operating supplies as well as the end product, transport, emissions (wastes, waste water, gases) and heat losses.

LCAs were conducted for some switchgear examined in Section 6. Table 45: gives an overview of the influencing variables assumed in these LCAs. Table 46: shows the results of the studies. **Due to the high number and lack of transparency in the required influencing variables or boundary conditions, the LCAs cannot be reproduced with the current level of knowledge and hence a direct comparison between the different manufacturers is not possible.** It is impossible to make a universal comparison of LCAs, particularly because of variably accepted parameters like lifetime, gas loss, attribution of gas losses to material, production and transport.

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At the same time, the different manufacturers force a comparison of their SF_6 GIS with their SF_6-free alternative. The total effect on the environment is defined via the CO_2 equivalent over the complete life cycle. However, the studies do not specify any absolute values for the CO_2 equivalent, but instead only percentage improvements as compared to the SF_6 alternatives.

The calculated environmental potential of an installation is extremely sensitive to the assumed SF_6 emissions during production, operation and disposal. The manufacturers assume SF_6 leakage rates of approx. 0.1% over the entire life cycle. This value lies below the IEC standard (0.5%), below the IPCC value (2.6% including handling losses and malfunctions) as well as below the value of a study for the French current system (approx. 1%, [Dullni et al., 2015]) (see here also Section 3). Even below the SF_6 leakage rates of approx. 0.1% assumed (optimistically) by the manufacturers, the contribution of SF_6 emissions to the entire environment potential is approx. 45-77%.

In addition, the influence of the category 'Material/Production/Transport' on the environment balance for SF_6-free installations is only negligibly higher (ABB) or even lower (GE, Siemens) than for SF_6 installations. The category 'Material/Production/Transport' in Table 45: also accounts for SF_6 losses in the production of gas and switchgear for products from Siemens and GE. In the case of Siemens and GE, the increased need for steel/aluminium for SF_6 installations is more than compensated for, due, among other things, to the elimination of SF_6 emissions in the production of switchgear and SF_6 itself, in terms of CO_2 equivalence.

Under the assumptions made, the respective SF_6-free products enable a clear reduction of the environment potential of HV switchgear between 30-70% as specified by the manufacturers.

Table 45: Comparison of selected assumptions and input variables for LCAs of different SF_6 and alternative gas-insulated switchgear (GIS) of European producers for high voltage
Source: Own research based on [Presser et al., 2016] and interviews

<table>
<tr><th>Assumptions and input variables</th><th>ABB SF_6</th><th>ABB AirPlus</th><th>GE SF_6</th><th>GE g^3</th><th>Siemens SF_6</th><th>Siemens Clean Air</th></tr>
<tr><td>Lifetime (in years)</td><td>30</td><td>30</td><td>40</td><td>40</td><td>50</td><td>50</td></tr>
<tr><td>Current mix</td><td colspan="6">European current mix</td></tr>
<tr><td>Load profile</td><td colspan="2">100% of the time 50% rated current</td><td colspan="2">80% of the time 25% rated current, 20% of the time 60% rated current</td><td colspan="2">100% of the time 50% rated current [Presser et al., 2016]</td></tr>
<tr><td>Gas losses (rate of leakage)</td><td>0.1% per year</td><td>0.1% per year</td><td rowspan="3">0.2% per year</td><td rowspan="3">0.2% per year</td><td>≤0.1% per year</td><td>≤0.1% per year</td></tr>
<tr><td>Gas losses (recycling)</td><td>1%</td><td>1%</td><td>0.01%</td><td>0.01%</td></tr>
<tr><td>Gas losses (maintenance)</td><td>1% per service life</td><td>1% per service life</td><td>0.01% per service</td><td>0.01% per service</td></tr>
<tr><td>Service intervals (years)</td><td>Not specified</td><td>Not specified</td><td>Not specified</td><td>Not specified</td><td>25</td><td>25</td></tr>
</table>

Table 46: Influence of gas emission, heat loss and material on the total CO_2 equivalent of HV switchgear through various methods applied GE and Siemens consider emissions from SF_6 production and producer phase of the installations.
Source: Own research based on [Presser et al., 2016], [Gautschi, 2016] and interviews

<table>
<tr><th>Influence of environmental factors on the environment potential [%]</th><th>ABB SF_6</th><th>ABB AirPlus</th><th>GE SF_6</th><th>GE g^3</th><th>Siemens SF_6</th><th>Siemens Clean Air</th></tr>
<tr><td>Gas emissions</td><td>45%</td><td>0%</td><td>67%</td><td><1%</td><td rowspan="2">77%</td><td rowspan="2">51%</td></tr>
<tr><td>Heat loss</td><td>46%</td><td>38%</td><td>6%</td><td>6%</td></tr>
<tr><td>Material/Manufacture/Transport</td><td>9%</td><td>12%</td><td>27%</td><td>23%</td><td>23%</td><td>17%</td></tr>
</table>

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