Abatement cost of SF_6 emissions from medium voltage switchgear

Validation of recent studies for the European Commission

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Further information on this study can be obtained from the contact person, Jos Benner.

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CE Delft is an independent research and consultancy organisation specialised in developing structural and innovative solutions to environmental problems.
CE Delft's solutions are characterised in being politically feasible, technologically sound, economically prudent and socially equitable.

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Summary

Sulphur hexafluoride (SF_6) is a gas with applications including use as an insulator and switching medium in medium voltage (MV) switchgear. While having certain unique properties, it is also a greenhouse gas, with a 22,800 times greater impact than CO_2 and an atmospheric lifetime of over 3,000 years.
Although the use of SF_6 in MV switchgear can be avoided, according to recent studies for the European Commission by Öko-Recherche et al. the abatement costs are high. This study validates the calculated cost levels as well as the general feasibility of determining a fixed cost figure for this purpose.

CE Delft has analysed the full life cycle emissions of SF_6 used in MV switchgear as well as the costs of both switchgear employing SF_6 and SF_6-free alternatives. To this end CE Delft supplemented its own expertise with desk research, interviews, analyses and validation of existing literature and contacts with industry experts and scientists. This analysis yields a result which differs from the earlier studies, particularly with respect to the cost aspect, but also in other areas.

Based on the available data, CE Delft found that it is impossible to specify a definitive figure for the full life cycle emissions of SF_6 used in MV switchgear. There are major differences in both production processes and in the quantities of SF_6 used in different types of MV switchgear. For good-quality units, the most plausible bandwidth for life cycle SF_6 emissions is between 7 and 22%, with higher values holding for insufficiently gas-tight units and lower values achievable under optimum conditions. The Öko-Recherche reports indicate just one fixed level of a little under 10%.
As the Öko-Recherche emission calculation is based on a type of MV switchgear with a relatively low SF_6 content (12 kV RMU) they report an SF_6 emission level of just under 70 grams per panel. For the actual emissions of all types of MV switchgear CE Delft arrives at a bandwidth of 40 to 660 grams per panel, representing 1 to 15 tonne CO_2 equivalents.

There is even a bigger difference in the findings with respect to costs. Öko-Recherche reports extra costs of € 300.00 per panel, implying relatively high emission abatement costs. The available data indicate that the investment costs for most SF_6-free installations are lower than those of SF_6-containing switchgear, which would yield negative abatement costs.

CE Delft also takes a number of other cost aspects into account that were not considered by Öko-Recherche, the most important of which is maintenance. There are indications that, for higher voltage levels (over 25 kV) and under severe site conditions, well-sealed SF_6 units may have lower maintenance costs and a longer lifespan. To what extent this effects the abatement cost level could not be determined based on currently available information.

CE Delft concludes that for the majority of applications cost-effective SF_6-free options are available, leading to abatement costs for the use of SF_6 in MV switchgear that range from - 40 to 0 €/tCO_2 eq., for all types of switchgear, with voltage levels below 25 kV and situated on relatively dry locations. This might also be true for cases with voltage levels over 25 kV and for switchgear used under severe site conditions, but this cannot be concluded from the present study, since data on the precise differences in maintenance costs and lifespan are lacking.

1 Introduction

This introduction sets out the aim and the structure of the report and provides information on the context and methodology of the study.

1.1 Context and aim

Among the greenhouse gases covered by the Kyoto Protocol are three groups of fluorinated greenhouse gases (the so-called 'F-gases'): hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). In the European Union emissions of these gases are controlled under two pieces of legislation: the F-Gas Regulation and the MAC Directive.

The European Commission is currently reviewing the application, effects and adequacy of the F-Gas Regulation. The Commission is required to present appropriate proposals for revision of the relevant provisions of the regulation. To that end, the European Commission ordered a preparatory study into the potential for additional policy measures (Öko-Recherche fin, 2011).

The present report, by CE Delft, focuses on sulphur hexafluoride, which is probably the least known of the Kyoto greenhouse gases. It is a gas with unique properties, which is used, among other applications, in the metal industry and in medium and high voltage switchgear. It is a colourless, odourless, non-flammable, non-toxic, non-corrosive, man-made gas that is chemically inert. It has good insulating properties and it quenches (electrical) arcs.
SF_6 is also a greenhouse gas with a high specific impact on the global climate system. Its specific greenhouse impact is 22,800 times greater than carbon dioxide (CO_2) and because it is so extremely inert, once released into the atmosphere it continues to affect the climate for over 3,000 years. There are no natural sources and no natural removal processes.

Under the existing F-Gas Regulation, several minor applications of SF_6 have been prohibited: use in double glazed windows, in shoes and car tyres, and as a cover gas in magnesium die-casting. However, most (> 80%) of the SF_6 produced is used in high and medium voltage switchgear.

In assessing the potential for additional policy, one of the relevant criteria are the abatement costs, i.e. the costs of avoiding SF_6 emissions. These are generally expressed in euro per tonne avoided emission (€/t) and then converted to euro per tonne CO_2 equivalent (€/tCO_2 eq.)so they can be compared with the abatement costs of other options.

This report focuses on the use of SF_6 in medium voltage (MV) switchgear and on the abatement costs for this particular application. Abatement is feasible, since compact SF_6-free MV switchgear is now widely available and on offer from all larger switchgear manufacturers. As an insulator, SF_6 is replaced by air or solid insulation materials, as a quenching medium by a vacuum chamber or polymer. For high voltage applications (> 50 kV) SF_6-free alternatives are still under development.

According to the preparatory study for a review of Regulation No. 842/2006,commissioned by the European Commission (Öko-Recherche et al., WDR3, 2011), the abatement costs for use of SF_6 in MV switchgear vary between 33.9 and 347.3 €/tCO_2 eq., depending on the chosen perspective. The aim of the present report is to validate this value. The validation considers both the absolute level of these costs and the feasibility of obtaining such an absolute value.

1.2 Methodology and report structure

In the present study all the stages of the life cycle of SF_6 used in MV switchgear were analysed, from production/synthesis of the SF_6 gas all the way through to decommissioning of the switchgear and processing of the residual gas. Throughout this analysis, the same steps and units were applied as in the Öko-Recherche report. This yields an estimate of the SF_6 leakages occurring over the full life cycle of the SF_6 used in MV switchgear.

The results are based on the expertise of CE Delft, complemented by desk research, interviews, analyses and validation of existing studies and literature and contacts with industry experts and scientists. Cost differences between use of SF_6 in MV switchgear and alternatives were analysed mainly on the basis of contacts with producers and users of both SF_6-containing and SF_6-free MV switchgear. In this way a bandwidth was obtained for the abatement costs of avoided SF_6 emissions, expressed in both euro per tonne avoided emission (€/t) and euro per CO_2 equivalent (€/tCO_2 eq.).

Chapter 2 starts out by discussing some of the specific terms used in this field and briefly considers several issues relating to on technical parameters, cost levels and legislative developments. In Chapter 3 the emission data for the various phases in the life cycle of SF_6 used in MV switchgear are analysed and the resultant emissions bandwidth is presented. Chapter 4 discusses the differences in costs between SF_6-containing and SF_6-free equipment. In Chapter 5 these data are used to validate the abatement costs for the use of SF_6 in MV switchgear reported in the preparatory study for the European Commission.

2 Facts and figure

This explanatory chapter looks at some of the specific terms used in this field and considers several issues relating to technical parameters, cost levels and legislative developments.

2.1 Medium voltage switchgear

The switchgear sector is divided into three segments: high voltage (HV, > 52 kV), medium voltage (MV, 1-52 kV) and low voltage (LV, < 1 kV).Two types of medium voltage (MV) equipment are generally distinguished:
- primary MV switchgear at the interface with high voltage;
- secondary MV switchgear at the interface with low voltage, most of which consists of so-called ring main units (RMU): systems in transformer stations for the switching of cables and protection of the transformer.

In most cases, an RMU unit comprises three SF_6-filled compartments ('panels' or 'feeders'), two of which are for the cables and one for the transformer. Primary switchgear and other non-RMU secondary switchgear may consist of anything between 2 and 40 panels.
Before 1980 the use of SF_6 in MV switchgear was rare, but SF_6 is now applied in all types of MV switchgear. In Europe (EU 27) almost 3 million SF_6-containing MV installations are currently in operation.

2.2 Market distribution

There are no official figures, nor independent verifiable sources on the market share per type of MV switchgear. Based on information from different experts we conclude that about 70% of the MV switchgear in Europe is secondary equipment and about 30% primary. The market share per voltage level is 12 kV: 60%, 24 kV: 30% en 36 kV and higher: 10%. In SF_6-containing installations the amount of SF_6 varies between 0.6 and 3 kg per panel, increasing with voltage level.

The SF_6 gas in MV switchgear is used for insulation and/or as a switching medium, to quench electrical arcs. One of the reasons most frequently cited for opting for SF_6 is the size of the equipment: MV switchgear with SF_6 is often claimed to be more compact. Conversely, however, this does not mean that SF_6-free switchgear is necessarily bigger. Today, compact SF_6-free MV switchgear is widely available on the market and produced by a wide range of manufactures.

2.3 Development of legislation around SF_6

The need to reduce SF_6 emissions is recognised the world over and is being tackled at several policy levels. At the global level, SF_6 is included in the Kyoto Protocol because it has a greenhouse impact that is 22,800 times greater than CO_2 and an atmospheric lifetime and thus climate impact of over 3,000 years.

The European Union, for its part, seeks to control SF_6 emissions by way of the F-Gas Regulation (EU Commission, 2006), the adequacy of which is currently being reviewed by the European Commission. In order to elaborate an appropriate proposal for revision of the relevant provisions (foreseen for autumn 2012) the Commission commissioned a study into the potential for additional policy measures.

Individual EU member states have also taken action. Denmark has a tax on SF_6 of about 53€/kg (with some exemptions). In France, Germany and Spain there are voluntary agreements addressing the use and emissions of SF_6 in switchgear.

In the USA the Environmental Protection Agency employs a voluntary code of practice and voluntary partnerships with industries as a major tool for reducing F-gas emissions. 'Responsible use' guidelines seek to reduce manufacturing emissions, including those from aluminium manufacture, magnesium production, semiconductor and electrical power industries.

On July 1st 2012 Australia is to introduce a 'carbon-equivalent tax' that will also cover SF_6. The tax is 23 Australian dollar/tCO_2 eq., equivalent to 17.9 €/tCO_2 eq. For SF_6 the tax will be 408,120 €/t SF_6 (Australian Government, 2012).

2.4 Voluntary agreements between government and industry

The industry reports a trend towards voluntary emission reduction. Voluntary agreements between government and industry on a national level are already in place in Germany, France, Norway, Spain and Switzerland. A summary of these agreements is appended to the whitepaper of T&D Europe (T&D Europe, 2011). These agreements differ substantially with respect to the period covered, the level of ambition expressed and the reported results; see Table 1.

None of these voluntary agreements take into account the emissions associated with SF_6 synthesis and transport to switchgear production sites. The German agreement is the most specific and ambitious. It is also the only agreement that differentiates between targets for the life cycle of HV and MV equipment.

Table 1 Summary of voluntary agreements between industries and national governments

Country	Germany	France	Spain	Norway	Switzerland
Date	May 2005	2004	March 2008	March 2002	August 2008
Period	2004-2020	1995-2010	2008-2012	2000-2012	
Overall targets	23% absolute emission reduction in 2020 22 t/y (2004) => 17 t/y (2020)	-	Relative emission reduction of 300,000 t in 2012 compared to 2006	30% emission reduction in 2010 compared to 2000	-
Production	< 1.6&/y	-	-	-	-
Use	< 0.2%/y	-	-	-	-
Decommissioning	< 2%	-	-	-	-
Achievements as reported by industry	38% overall reduction in 2009 (14 t in 2009) 50% reduction in production phase in 2009 compared to 2004	50% reduction in production phase in 2009 compared to 1995 (HV and MV together)	30% relative overall reduction in 2009 compared to 2006 (HV and MV together)	50% overall reduction in 2010 compared to 2000 (HV and MV together)	-

2.5 The preparatory study for the F-Gas review

In the preparatory study, technical data and analyses were presented to the European Commission for all F-gases. As a part of the work, Öko-Recherche presented the abatement costs for SF_6 in MV switchgear, reporting them to be 33.9 or 347.3 €/tCO_2 eq., depending on the chosen perspective. These figures were calculated on the basis of the assumptions and calculation methods described below. In the following chapters these assumptions and calculations will be validated.

2.5.1 Cost assumptions in the preparatory study

In most MV switchgear containing SF_6, the gas is used for insulation and switching. Insulation in SF_6-free equipment relies on solid materials and/or air, which according to the Öko-Recherche report are associated with higher costs.

The cost differences, per panel, between an SF_6-filled Ring Main Unit (Gas Insulated Switchgear – GIS) and an SF_6-free alternative (Air insulated Switchgear – AIS) as stated by Öko-Recherche are shown in Table 2. These figures apply to a typical 12 kV RMU unit, which has a relatively low SF_6 content. In the Öko-recherche report the comparison is not made for other types of units or for other voltage levels.

Table 2 Overview of cost differences for a 12 kV RMU unit according to Öko-Recherche

		GIS (with SF_6)	AIS (SF_6-free)
Gas charge	kg	0.7	0
Basic investment cost	€	1,300	1,300
Capital investment per unit	€		13
Gas cost, first fill	€	11	
Vacuum chamber	€		250
Solid insulation + field control	€		20
Transformer protection	€		25
Total investment cost	**€**	**1,311**	**1,608**
Lifetime expectancy	Years	40	40
Discount rate	%	4%	4%
Annual investment cost	€/yr	66.21	81.24
End of life costs	€/yr	2	
Annual total cost	€/yr	68.21	81.24

The investment costs for an SF_6-free unit are stated by Öko-Recherche to be € 297 higher, per panel, than the € 1,300 for the SF_6 reference unit. On top of this, capital investment costs (of 1% per unit) are added, on the argument that the costs of SF_6-free units will rise if more manufacturers opt for the AIS, as a consequence of the required conversion of production lines. On an annual basis (40 years lifetime), the additional cost then amounts to about € 13 (including interest).

2.5.2 Emission assumptions in the preparatory study

The precise emission assumptions are not explicitly stated in the Öko-Recherche reports. Some analysis of the provided data makes clear, however, that Öko-Recherche assumes, for the reference 12 kV RMU unit, a total use of 790 gram SF_6 per panel. This figure is made up of 720 gram of SF_6 for initial filling of the unit and 70 gram of leakage over the various stages of the life cycle, from production of the SF_6 gas through to its processing after decommissioning of the switchgear unit.

The report calculates with an expected operational period for the switchgear of 40 years. Consequently, the 720 gram SF_6, for initial filling of the unit translates to an average of 18 gram per year. This 18 grams of SF_6 corresponds to approx. 400 kg of CO_2 equivalents. If the full SF_6 content of the switchgear unit were to leak into the atmosphere, as a consequence of an accident or careless deconstruction of the unit, this is the value to be used in abatement cost calculations. Öko-Recherche refers to this possibility in their 'demand abatement costs'.

The emissions of SF_6 that are certain to occur over the life cycle are assessed by Öko-Recherche at just under 70 grams. Spread out over 40 years, this corresponds to 1.7 gram per panel per year, or 38 kg CO_2 equivalents. This emission is referred to by Öko-Recherche in their 'emission abatement costs' the potential maximum total average annual SF_6 emission would amount to almost 20 gram, or more; the cited 790 gram divided by 40 (or a shorter lifetime in the case of accidents).

2.6 Abatement cost assumptions in the preparatory study

In the Öko-Recherche report the total extra costs and the emissions per panel are presented as annual figures. Based on the expected 40-year operational lifetime of the switchgear, the extra annual costs amount to € 13 (€ 300. spread over 40 years, including interest).
As stated above, the SF_6 used for initial filling of the panel translates to 18 grams per year, or approx. 400 kg of CO_2 equivalents. Consequently, abatement costs are 33.9 €/tCO_2 eq. in the Öko-Recherche report these are labelled 'demand abatement costs'. An overview, taken from this report, is presented in Table 3.

Öko-Recherche also present so-called 'emission abatement costs'. This calculation comprises only those leakages of SF_6 that can be said to be certain. For these emissions Öko-Recherche calculates an abatement cost level of 347 €/tCO_2 eq., based on an estimated annual leakage of 1.7 gram SF_6 per panel (38 kg CO_2 equivalent).

Table 3 Abatement costs in €/tCO_2 eq. and potential reduction in tCO_2 eq. according to the Öko-Recherche report ('demand' considers the full life cycle and 'emission' only SF_6 leakages during operation)

EU-27 – demand abatement vs. WM scenario in MV switch gear 2030 and 2050			
MV switch gear		2030	2050
abatement cost	€/tCO_2eq	33.9	33.9
demand reduction	ktCO_2eq	3,103	3,103
EU-27 – emissions abatement vs. WM scenario in MV switch gear 2030 and 2050			
MV switch gear		2030	2050
abatement cost	€/tCO_2eq	347.3	347.3
emissions reduction	ktCO_2eq	97	232

3 Emissions of SF_6

In this chapter the different life cycle phases in the use of SF_6 for MV switchgear are analysed, from synthesis of the gas through to its processing after decommissioning of the switchgear unit. For each phase, emission figures are discussed. By way of conclusion the resulting bandwidth in emission levels is presented and translated into tonnes of CO_2 equivalents.

Four major phases can be distinguished in the use and emissions of SF_6 for MV switchgear:
1. Synthesis and transport of the SF_6 gas.
2. Production and installation of the MV switchgear.
3. Use of the MV switchgear.
4. Decommissioning of the MV switchgear.

Table 4 summarises relevant data on the SF_6 emissions occurring during the last three of these phases, as available from the literature. These data are elaborated upon in the following sections.

Table 4 Emission factors of SF_6 by MV switchgear, as a percentage of quantity used

Source*	Production (%)	Use (%/year)	Decommissioning (%)
Ecofys, 2010			
- BAU**	3%	1%	0.9%
- BAT**	2%	0.4%	0.9%
Ecofys, 2005			
- Sealed	3%	0.1%	2%
- Closed	3%	0.5%	2%
Mersiowsky, 2003			
	No indication	0.14%	2%

*: Source details can be found in the references.
**: BAU: business as usual; BAT: best available technology.

The analysed reports contain no data on the emission occurring during the synthesis of SF_6. However, useful data are provided in IPCC's 'Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories'.

3.1 Emissions due to synthesis and transport

Within the framework of this study it was not possible to obtain adequate data from the industry on the emissions due to SF_6 synthesis and transport. However, the IPCC's 'Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories' (IPCC, Corrigendum, 2001) states that the SF_6 emissions of associated with SF_6 synthesis should be set at 0.1% +/- 0.05% per year. This figure applies to SF_6 production in a dedicated continuous process with optimised closing valves to minimise leakage when filling transport cylinders. In suboptimal situations this figure will be too low. The same guidelines recommend setting transport-related emissions at 8% per year. These emissions derive, inter alia, from insufficient emptying of the tanks in which the SF_6 is transported from the production site to the installation where it is being applied.

This emission figure seems to be based on the former industry standard of 50 mbar evacuation pressure. The Japanese and European industry claim to have switched to a new standard of 15 mbar evacuation pressure, which will lead to lower residual concentrations in the transport tanks. The new voluntary IEC standard 62271-4 (IEC, 2012) requires an evacuation pressure of below 20 mbar, corresponding to a maximum residual concentration of about 2%. In current practice, therefore, transport emissions will probably be lower than the cited figure of 8%.
Data on the magnitude of emissions due to incidents and accidents during synthesis and transport were not available from the industry.

3.2 Leakage rates during switchgear production

Production covers the testing and the filling of the MV equipment and the transport of the switchgear to the customer, with possible additional filling and evacuation. The associated leakage is estimated at 3% for business as usual (BAU) and 2% for the best available technology (BAT); see Table 4.
The main moments with leakage are:
- filling of the SF6 MV switchgear;
- testing of equipment, requiring additional filling and evacuation;
- topping up and gas recovery during transport of the equipment.

3.2.1 Filling
Modern factories have a central supply system for SF_6 gas, with pipes to individual workstations. This allows for central monitoring of gas use. Contrary to the ‘bottles’ formerly used, however, these piping systems initially lacked self-closing valves. According to the industry, though, self-closing valves have today been installed in most cases (Ecofys, 2005). However, attempts to track down the penetration level in publicly available sources were unsuccessful.

3.2.2 Testing
A second source of SF_6 emissions is the evacuation of equipment after testing. Emissions due to evacuation depend on the minimum pressure achievable by the evacuation equipment. Until recently SF_6 gas equipment was evacuated to 50 mbar, resulting in an emission of 4.3%. Manufacturers claim that under the voluntary agreements between government and industry in some EU member states they switched from testing SF_6 MV equipment with SF_6 gas to testing it with helium gas. This should both ensure better gas tightness (helium molecules are smaller than SF_6 molecules and therefore more likely to escape) and avoid an additional emission source during evacuation of the gas after the test cycle. However, the producing industry was not able to provide us with data on the degree of penetration of testing with helium instead of SF_6.
The current voluntary industry standard requires evacuation to 15 mbar, which would result in an emission of 1.3% (ABB, 2012; T&D Europe, 2011).

3.3 Leakage rates during the operational phase

The data on SF_6 leakages reported for the operational phase of the switchgear consider all the emissions of SF_6 from the moment the equipment is installed until it is decommissioned. For sealed-for-life equipment, data on the emission of SF_6 occurring during this phase can be estimated from the outcomes of mandatory leakage rate tests. Under IEC standards, manufacturers of SF_6-containing MV switchgear must demonstrate that the leakage rate of their equipment is sufficiently low to ensure a lifetime of 20, 30 or 40 years. This generally means that less than 10% of the SF_6 content may leak away during that period. This implies a maximum average annual leakage rate of 0.5% or 0.25% per year to guarantee a life time of 20 or 40 years, respectively. It should be noted that these tests are executed under laboratory conditions and with new equipment. In the context of this study it was not possible to track down publicly available data comparing the emissions occurring during such laboratory test with those under 'real life' conditions. The industry claims, however, that in Europe and Japan actual emissions are lower then those required in the tests: 0.1% (Ecofys, 2005; Mersiowsky, 2000).

3.3.1 Leakage rates under on-site conditions

The above-mentioned leakage rate tests are performed under lab conditions with a constant reference temperature of 20 degrees Celsius. In practice, though, the switchgear must function under more severe conditions. The Belgian research institute Laborelec, in cooperation with three Belgian Distribution Network Operators (DNOs), has developed an alternative test that includes a temperature cycle resembling the on-site conditions of secondary switchgear in Belgium. The results apply to sealed–for-life secondary switchgear situated in prefabricated epoxy housings. This test was applied to a range of different types of switchgear. The outcomes indicated leakage rates varying from 0.05% to 0.9% per year. Two of the five different types tested (i.e. 40%) showed a leakage rate too high to guarantee safe operation over the indicated lifetime.

3.3.2 Leakage rate for decommissioning

Emissions during decommissioning comprise the emissions occurring from the moment the MV switchgear is decommissioned until the gas is reused or destructed in a specialised facility.

For the producers approached for this study, evacuation of the MV switchgear is part of the standard decommissioning procedure for SF_6 switchgear.

As cited above, the current industry standard is stated to be evacuation to below 15 mbar, resulting in an emission below 1.3% (ABB, 2012; T&D Europe, 2011). This voluntary standard is incorporated in the new IEC standard 62271-4, expected to enter into force in 2012. The IEC standard applies to all those working with SF_6. Since small additional emissions are possible in the reuse (< 0.3%) or destruction phase (< 0.5%), this sums to a maximum of 2% for the current industry standards.

3.4 Conclusions on SF6 emissions over the full life cycle

The findings of CE Delft on the SF_6 emissions over the full life cycle are summarised in Table 5.

Table 5 Conclusions on the emissions over the total life cycle

	Synthesis & transport (%)	Switchgear production (%)	Switchgear operation (%)*	Decommissioning (%)	Total life cycle (%)
Sufficiently tight equipment	2.5 - 8 (0.5-8)**	2-3	2-8.8	0.5-2	**7-22 (5-22)****
Remarks on these values	Lower values only for BAT processes and BAT tank evacuation. Accidents not included.	Lower values only for BAT SF_6 piping and valves. Testing with helium. No topping.	Lower values only for best available products.	Lower values only for BAT processes and BAT tank evacuation. Accidents not included.	
Estimate for non-sufficiently tight equipment/ extra transport losses	3.5-9	2-3	9.2-36	1-2	**15.7-41**

*: Based on 40 years life time.
**: Possible under optimal conditions.

From the above it may be concluded that:
- No specific data were found on emissions during SF_6 synthesis. The figure assessed by IPCC for the synthesis process is below 0.2%. The emission estimated for the transport phase is up to 8 %. A plausible level based on existent standards is 2%, but under optimal conditions transport losses may be as low as 0.5%.
- Emissions during switchgear production vary, depending on how the SF_6 is handled and how testing is organised. The reported overall figure of below 3% for the production phase seems reasonable.
- Emissions during the decommissioning phase add up to an overall figure of below 2%.
- Under on-site conditions the average annual leakage rate for different types of MV secondary switchgear vary between 0.05% and 0.9% per year.

The most plausible emission over a lifetime of 40 years ranges from 7 to 22% for all types of MV switchgear that meet the mandatory tightness requirements. Under optimal conditions a figure of 5% – or even less - can be achieved by producers performing better than the international standards. At the other end of the spectrum, field tests by Tits and Delouvroy (Laborelec, 2011) showed that a significant fraction of the secondary equipment on the market has a higher emission rate than the cited figure of 22% (up to 41%).

3.5 Emissions in tonne CO_2 equivalent

As mentioned in Chapter 2, the amount of SF_6 in MV switchgear varies from 0.6 to 3 kg per panel, depending on the type of unit and the voltage level. Based on emission rates for sufficiently tight equipment, this means that the most plausible figure for the amount of SF_6 potentially leaking from a panel over its total life cycle is between 40 and 660 grams, depending on the degree of leakage and the type of product. This is equivalent to between 1 and 15 tonne CO_2 equivalents.

Based on the cited figures, which are estimates derived from the best available data, an estimate can be made of the total amount of SF_6 that is likely to have leaked to the atmosphere over the past few decades as a result of its use in switchgear. However, the SF_6 concentrations of actually measured in the atmosphere are far higher than this estimate points to, which might well indicate that actual emissions were or are higher (Levin et al., 2010; Maiss and Brenninkmeijer, 1998; Rigby, 2010). Further analysis of the differences between the relevant measurements and the emission data reported by the SF_6 consuming and producing industry could shed more light on this matter.

4 Cost parameters

In this chapter the various issues determining the cost differences between SF_6-filled and SF_6-free MV switchgear are discussed. As described in Chapter 2, there are many different types of MV switchgear, and in general there is an SF_6-free alternative for each. Even alternatives for high voltage applications up to 150 kV are under development. The discussion on the applicability of these alternatives revolves round the following themes: safety, size, maintenance, lifetime expectancy and market share.

As a preliminary remark, it should be noted that it is in fact impossible to undertake a full comparison of switchgear options with and without SF_6, since apart from the SF_6 aspect they always have other technical differences as well as different requirements for accessories and so on. In the following discussion these differences are dealt with as objectively as possible.

4.1 Safety and end of life costs

Up to the 25 kV voltage level, no safety limitations were found with regard to the use of SF_6-free alternatives. Some parties expressed concern about the possibility of virtual current chopping in the vacuum circuit breaker (VCB) at voltage levels over 25 kV, leading to possible damage. They fear that under extreme conditions current chopping may go more violently wrong in a VCB than in switchgear using SF_6 for arc-quenching. The relevance of this fear is unclear.

A final pronouncement on this issue is beyond the scope of this study. However, the fear is put into some perspective by the fact that Hitachi & Toshiba Japan has a 145 kV VCB unit in service, while Siemens has a 145 kV VCB unit in development.

Switching in SF_6-filled equipment has its own hazards and consequences. The likelihood of the formation of very hazardous reaction products, including disulphur decafluoride (S_2F_{10}, a highly toxic gas, with a toxicity similar to phosgene) increases with the voltage level (Solvay Fluor; Schneider Electric, 2003). The potential occurrence of these very hazardous toxics creates additional direct and indirect costs, including the training of certified handlers, safety precautions and systems, additional handling requirements (under EU legislation, spent SF_6 is considered to be hazardous waste) and longer waiting times after an incident (due to the necessary reconnaissance for potentially dangerous products), which means that end-users suffer longer outage and consequent production losses. These cost elements, which could be relative significantly, are outside the scope of this study, however.

For the producers consulted for this study (ABB, 2012; Siemens, 2012), evacuation is part of the standard procedure when decommissioning SF_6 switchgear. This requires a maximum of one hour additional work (i.e. € 35), to which the costs of handling and recycling the SF_6 must be added. Producers claim that the gas from MV switchgear is so clean after its lifetime that mild filtering is sufficient to allow reuse, in contrast to the SF_6 used in HV switchgear, which requires cryogenic separation techniques before it can be reused.

4.2 Dimensions

Because secondary equipment/ring main units are often installed in locations where floor surface is scarce or expensive, size matters, and SF_6 circuit breakers are often claimed by producers to be more compact. However, similar and very compact SF_6-free alternatives do exist. SF_6-free switchgear with a floor area of 0.2 m^2 is already available (not taking into account the much smaller Magnefix units with a floor surface of 0.06 m^2) (ABB, 2010; Driescher, 2012; Eaton Holec, 2012).

4.3 Maintenance

Maintenance-related costs are often cited as an argument for using SF_6 equipment. An interesting distinction can be made between equipment installed under relatively moderate climate conditions (dry, temperature varying between 10 and 30°C, normal air composition) and equipment that must function under severer conditions (wet floors, high ambient concentrations of salt or corrosive chemicals in the air, temperatures well below 10°C).

The first case is relevant for switchgear installed indoors and ring main units situated close to a transformer, which will keep it warm and dry. This applies to all primary MV switchgear and to over half of secondary switchgear. In this case the maintenance costs are the same for SF_6-containing units and SF_6-free units and – as explained in Section 4.1 - since additional precautions need to be taken in the case of use of SF_6, overall maintenance costs are probably higher for the former. In the second case the maintenance costs may be higher for the SF_6-free units.

4.4 Life expectancy

The life expectancy of MV switchgear depends on numerous aspects that may or may not be (in)directly related to the use of SF_6. Two aspects are most clearly related to SF_6:

- *Sensitivity to surrounding conditions*
  Producers of SF_6-filled equipment claim that the stainless steel tank that contains the SF_6 gas will also protect against decay due to ambient conditions like moisture, dirt and corrosives in the air, which might influence contacts and the dielectric strength and cause creepage currents, leading to unsafe operation or even explosions. Producers of SF_6-free equipment dispute this argument, claiming that their enclosure and protection levels are equally sound because all primary HV components are protected by a sealed enclosure as well.
- *SF_6 leakage rate*
  In SF_6-filled equipment leakage may cause insufficient isolation (i.e. dielectric strength and creepage currents), leading to unsafe operation and/or explosion and the possibility of formation and leakage of hazardous reaction products of SF_6 (Laborelec, 2011).

The tightness of the seals of the SF_6 compartments is crucial for life expectancy. As discussed in Section 3.3, though, leakage rates may vary considerably under different on-site conditions.

Commissioned by the Dutch distribution network organisation Enexis, KEMA has tested several types of MV switchgear. Based on the outcomes of that study under difficult circumstances (elevated water levels, high concentrations of corrosives in the air, low temperatures) for specific types of SF_6-containing MV switchgear a life expectancy of over 50 years is held to be justified, whereas SF_6-free alternatives have a life expectancy of 35-40 years under these ambient conditions.

4.5 Scale of production

The scale of production will have effect on production costs. A larger scale of production allows for dedicated production lines, using robots to do part of the work, for instance, and thus saving on labour costs in production. For example, in Germany, annual output of SF_6-containing 12 and 24 kV RMUs is currently four times higher than that of SF_6-free units, which could explain the 20% lower price of the former when manufactured in Germany. That this is due predominantly to the scale of production may be demonstrated by the fact that at the same time there is no significant price difference between 36 kV RMUs with or without SF_6.

Based on quotations received, four installation companies in the Netherlands report lower prices for all SF_6-free switchgear than for SF_6-containing alternatives. The actual influence of production scale on cost price requires further investigation.

4.6 Conclusions on costs

Even though an absolute comparison of the switchgear options is unfeasible, since they always also differ with respect to more than just the SF_6 aspect, no evidence could be found that SF_6–free MV switchgear is more expensive than switchgear containing SF_6. In point of fact,SF_6–free switchgear generally appears to be up to 10% cheaper than the corresponding SF_6–containing alternative.

For voltage levels above 25 kV, safety issues may lead to a preference for SF_6–filled units. However, the absolute need for SF_6 in this voltage range is unproven.

Under severe climate conditions SF_6–free MV switchgear may require extra maintenance and thus have higher costs. On the other hand, switching in SF_6 may lead to the formation of hazardous reaction products and extra end of life processing costs. The exact influence of these factors on the total costs could not be determined within the framework of the present study.

5 Validation of abatement costs

Using the data and insights on emissions and costs presented and discussed in the previous chapters, this chapter now proceeds with actual validation of the SF_6 abatement costs associated with use of SF_6-free alternatives to SF_6-filled MV switchgear reported in the preparatory study by Öko-Recherche.

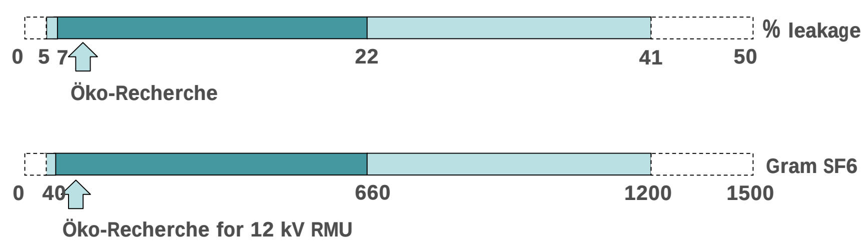
5.1 Validation of emission figures

The Öko-Recherche study reported emissions of almost 10% over the full life cycle of the SF_6 used in MV switchgear. Based on the available data, CE Delft found that for good-quality units the most plausible bandwidth for the life cycle SF_6-emission is between 7 and 22%, with higher values holding for insufficiently gas-tight units and lower values achievable under optimum conditions.

The most plausible current SF_6 emissions are between 40 and 660 grams per panel, representing 1 to 15 tonne CO_2 equivalents. This large bandwidth is due to differences in the characteristics and voltage level of the switchgear, plus circumstances during SF_6 synthesis and transport and filling, testing and evacuation of the switchgear. The amount of SF_6 in the equipment is an important factor. 12 kV equipment with 0.6-1 kg of SF_6 per panel will emit less than 36 kV equipment with 2-3 kg of SF_6 per panel.

For an average 12 kV RMU, of good quality and with 0.7 kg of SF_6 per panel, the study shows a most plausible leakage range varying from 40 to 154 gram of SF_6 over the full life cycle. Öko-Recherche reports a value of just under 70 grams. This value is relatively low, particularly because the 12 kV RMU has the lowest SF_6 content of all MV switchgear and also because a substantial share of SF_6-containing switchgear of lower product quality is on the market.

Figure 1 **Graphical presentation of the leakage range (dark part is the most plausible range)**



5.2 Validation of additional costs

The cost data analysis of the present study in fact points to an even greater difference from the data in the Öko-Recherche report, for it indicates that the purchase costs for most SF_6-free switchgear are lower than those of SF_6-containing units, which would yield negative abatement costs.

However, there is yet another relevant cost factor: maintenance, which was not considered by Öko-Recherche. There are indications that in this respect SF_6 units may perform better at higher voltage levels (above 25 kV) and on sites with severe climate conditions, leading to lower maintenance costs and longer life expectancy under such conditions.

On the other hand, there are likely to be extra end of life costs for SF_6-containing switchgear, arising from the required processing of (potentially) hazardous waste products. This factor was not taken into account by Öko-Recherche, either, just like the costs of the SF_6 itself.

Overall, though, there are insufficient data available to assess the impact of the maintenance and the end of life factors on abatement costs.

5.3 Validation of abatement costs

The analysis of CE Delft yields a different level of abatement costs over the full life cycle of the SF_6 used in MV switchgear than that presented by Öko-Recherche. The difference stems from both different emission figures and lower extra investment costs for SF_6–free units.

Abatement costs with Öko-Recherche cost figures

As stated above, no evidence was found for higher investment costs for SF_6–free units. However, for comparative reasons the extra investment costs presented by Öko-Recherche for the 12 kV RMU can be taken as a starting point. In that case the plausible emission bandwidth of 7 to 22 % would result in an emission abatement cost range of 170 to 520 €/tCO_2 eq. This range is based on € 300 extra investment plus interest costs, as calculated by Öko-Recherche.

If the interest costs are ignored, the bandwidth becomes 100 to 300 €/tCO_2eq. If an extra correction is included for the extra end of life treatment costs for SF_6–equipment and for the cost price of the SF_6, the bandwidth further decreases to 85 to 250 €/tCO_2 eq.

Abatement costs with CE Delft cost figures

Using both the emission data and extra costs from the CE Delft study the emission abatement costs for the use of SF_6 in MV switchgear are negative and range from - 40 to 0 €/tCO_2 eq. for all types of switchgear, with voltage levels below 25 kV and situated on relatively dry locations (e.g. indoors).

Figure 2 Graphical presentation of the abatement costs range (in €/tCO_2 eq.

This implies that for at least 60% of the EU market, cost-effective SF_6-free options are available (all primary equipment and over half of secondary equipment). To determine a fair abatement cost level for the other cases, operating with higher voltage levels or under more severe environmental conditions, additional research will be required.

References

ABB, 2010
Medium voltage Switching devices selection for application and purpose
Moorbank : ABB Australia Pty Limited, 2010

CORRIGENDUM, 2001
(GPGAUM-Corr.2001.01, 15 June 2001)
IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories
Available at: http://www.ipcc-nggip.iges.or.jp/public/gp/english/

EC, 2006
Regulation (EC) No 842/2006 of the European Parliament and of the Council of 17 May 2006 on certain fluorinated greenhouse gases
In: Official Journal of the European Union, 14-6-2006, L161/1- L161/11

Ecofys, 2005
Sina Wartmann and Jochen Harnisch
Reductions of SF_6 emissions from high and medium voltage electrical equipment in Europe, final report to CAPIEL
Nürnberg : Ecofys Germany GmbH, 2005

Ecofys, 2010
Jan-Martin Rhiemeier, Sina Wartmann, Marcello Pagnotta, Natalia Makowska, Xingyu Li
Update on global SF6 emissions trends from electrical equipment – edition 1.1: Ecofys Emission Scenario Initiative on Sulphur Hexafluoride for Electric Industry (ESI-SF6)
Cologne : Ecofys Germany GmbH, financially supported by JEMA, NEMA, ABB, Alstrom, Ormazabal, Schneider Eelctric, Solvay and Siemens

Equivalent carbon price, 2012-
Wesite: Equivalent carbon price for synthetic greenhouse gases
Canberra : Australian Government, Department of Sustainability, environment and Communities, 2012
Available at : http://www.environment.gov.au/atmosphere/ozone/sgg/equivalentcarbonprice/index.html

IEC, 2012
International Electrotechnical Commission
IEC 62271-4 Ed 1.0 : High-switchgear and controlgear - Part 4: Handling procedures for sulphur hexafluoride (SF6)
Geneva : International Electrotechnical Commission (IEC),2012

Laborelec, 2011
Yvan Tits and Giles Delouvroy (Laborelec), Joachim Marginet (Eandis), Alain Francois (Ores), Marcel Van den Berg (Sibelga)
Life time estimation of SF_6 MV switchgear according to on-site conditions in DNO's distribution networks
Paper (0971) at the 21st Int. Conf. on Electricity Distribution, CIRED, Frankfurt 6-9 June 2011

Levin et al., 2010
I. Levin, T. Naegler, R. Heinz, et al.
The global SF_6 source inferred from long-term high precision atmospheric measurements and its comparison with emission inventories,
In: Atmospheric Chemistry and Physics, no. 10 (2010); p. 2655-2662

Maiss & Brenninkmeijer, 1998
Manfred Maiss and Carl A. M. Brenninkmeijer
Atmospheric SF_6: trends, sources and prospects
In: Environmental Science & Technology, vol. 32, no.20(1998); p 3077–3086

Mersiowsky, 2003
Ivo Mersiowsky
SF6-GIS technology for Power distribution – Medium-Voltage – Summary Life Cycle Assesment,
S.l. : (Solvay Management Support) commissioned by ABB, AREVA T&D (formely Alstom), EnBW Regional, e.on Hanse, RWE, Siemens, Solvay Fluor und Derivate, 2003

Öko-Recherche, WDR3, 2011
Winfried Schwarz, André Leisewitz, Barbara Gschrey (Ökorecherche); Anke Herold, Sabine Gores (Öko-Institut), Irene Papst, Jürgen Usinger, Dietram Oppelt (HEAT International GmbH); Daniel Colbourne, Michael Kauffelt, Per Henrik Pedersen, Igor Croiset
Preparatory study for a review of Regulation (EC), No 842/2006 on certain fluorinated greenhouse gases Interim Report (working document 3)
Frankfurt/Main : Öko-Recherche GmbH, 2011

Öko-Recherche fin, 2011
Winfried Schwarz, Barbara Gschrey, André Leisewitz (Öko-Recherche GmbH), Anke Herold, Sabine Gores (Öko-Institut e.V.), Irene Papst, Jürgen Usinger, Dietram Oppelt, Igor Croiset (HEAT International GmbH), Per Henrik Pedersen (Danish Technological Institute), Daniel Colbourne (Re-phridge), Michael Kauffeld (Karlsruhe University of Applied Sciences), Kristina Kaar (Estonian Environmental Research Centre), Anders Lindborg (Ammonia Partnership)
Preparatory study for a review of Regulation (EC), No 842/2006 on certain fluorinated greenhouse gases, Final Report,
Frankfurt/Main : Öko-Recherche GmbH, 2011

Rigby et al., 2010
M. Rigby, J. Mühle, B.R. Miller, et al.
History of atmospheric SF_6 from 1973 to 2008
In: Atmospheric Chemistry and Physics, no. 10 (2010); p. 10, 10305-10320

Schneider Electric, 2003
D. Koch
Cahier technique no. 188 : SF_6 properties and use in MV and HV switchgear
Geneva : Schneider Electric, Direction Scientifique et Technique, 2003

Solvay Fluor
The SF_6 reuse process: a contribution on the sustainability of SF_6
S.l. : Solvay Chemicals

T&D Europe, 2011
SF_6 in electrical equipment of 1 kV to 52 kV (medium-voltage)
Statement on the review of Regulation (EC) No. 842/2006 of the European Parliament and of the Council according to Article 10 of 17 May 2006 on certain fluorinated greenhouse gases, Edition 1.0
S.L : European Association of the Electricity Transmission and Distribution Equipment and Services Industry (T&D Europe), 2011

Tomoe Shokai, 2012
Tomoe Shokai Co., Ltd.
Website: Prevention of global warming: Recovery and recycling of SF6
Available at: http://www.tomoeshokai.co.jp/english/showroom/sf6.html
Website visited on May 1st, 2012

Umweltrat, 2011
Pathways towards a 100 % renewable electricity system, special report
Berlin : SRU, German Advisory Council on the Environment, 2011
Available at:
http://www.umweltrat.de/SharedDocs/Downloads/EN/02_Special_Reports/2011_10_Special_Report_Pathways_renewables.pdf;jsessionid=440763E95C4919B41D340DCA8F009A6F.1_cid095?__blob=publicationFile

Personal Communication

ABB, 2012
Personal communication with Thor Endre, Sustainability Controller
ABB, April 2012

Alewijnse, 2012,
Personal communication with Will Coort, Technical Specialist
Alewijnse, Nijmegen, April 2012

Enexis, 2012
Personal communication with Johan Morren, Asset Manager, Enexis, April 2012

Siemens, 2012
Personal communication with Paul Hoorens, NWE RC-NL IC-LMV ARCH&PP, Siemens Nederland N.V.

Driescher, 2012 confidential
Overviews on dimensions of switchgear produced by Driescher. Provided by Christoph Driescher, Geschäftsführer, Elektrotechnische Werke Fritz Driescher & Söhne GmbH

Eaton Holec, 2012 confidential
Overviews on dimensions of switchgear produced by Eaton Holec. Provided by Wim Porte, Eaton Holec, May 2012