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IMPACT ASSESSMENT OF F-GAS FREE MEDIUM VOLTAGE SWITCHGEAR

Modeling scenarios of MV switchgear installation development and impact on SF6 emissions

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Modeling scenarios of MV switchgear installation development and impact on SF6 emissions

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in Kassel

Content

Executive Summary

Fraunhofer Institute for Energy Economics and Energy System Technology IEE and Grenoble Ecole de Management (GEM) have performed a research study to investigate the impact of the application of the greenhouse gas sulfur hexafluoride (SF6) in power distribution grids. The work was performed between March 2019 and April 2020.

The focus of the study is on medium voltage (MV) switchgear in electricity grids in the European Union. Participation in the study was open to all electricity grid stakeholders.

The study analyzes the application of SF6 and of fluorinated gas (F-gas) free alternatives in medium voltage grids and intends to support the COP 21 Paris Agreement, and industry's sustainability commitments towards the nature and the planet.

The study comprises two parts:

- modeling of MV switchgear installation development under different boundaries showing the impact on SF6 emissions,
- survey and choice experiment to analyze market acceptance of SF6-free alternatives, as well as barriers and drivers to adoption.

This report describes the approach and the outcome of the first part of the study.

Modeling scenarios of MV switchgear installation development and impact on SF6 emissions

We designed an asset-based model in a bottom-up, grid topology oriented approach for Germany, France and Spain and extrapolated to the EU28 countries. With that, we estimate that around 15 million MV switchgear functional units are installed today of which 10 million are using SF6. We estimate the banked SF6 volume in MV switchgear for EU28 today with 8600 t. This is equivalent to about 20% of the yearly greenhouse gas emissions of the EU28 power generation industry. The yearly operation emissions are 0.1% of the banked volume.

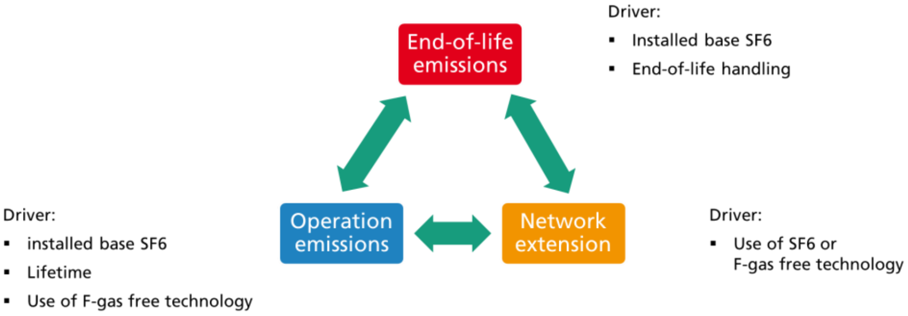
Table 1: Modeling results for number of MV switchgear and SF6 banked volume

Modeled installed Base 2020	Germany	France	Spain	EU28 (extrapolation)
Number of MV switchgear functional units – total [million]	ca. 3,1	ca. 2,0	ca. 1,7	ca. 15
Number of MV switchgear functional units – use of SF6 [million]	ca. 1,4	ca. 2,0	ca. 1,1	ca. 10
SF6 banked volume in MV switchgear [t]	1300	1100	1200	8600 (196 million t CO2 equiv.)

The model allows investigating the impact and sensitivity of variable parameters like grid extension, technology market shares, switchgear lifetime, or policy and regulation like forced replacement over the years until 2050 with an outlook to 2100.

Three main drivers define the development of SF6 emissions in medium voltage switchgear: network extensions, operation emissions, and end-of-life handling. The end-of-life handling has the key role. Network extension effects are also significant.

Figure 1: The three main drivers for SF6 emissions of switchgear in MV grids and substations



- We expect network extensions resulting in an increase of about 40% in MV switchgear installations until 2050 due to demand increase but mainly due to the increase in renewable energy installations.
  Provided a steady market share of SF6 applications this leads to the same increase of the banked SF6 volume and yearly operation emissions.
  - We recommend starting as soon as possible using F-gas free equipment wherever applicable to minimize network extension effects on greenhouse gas emissions.
- Considering the European Green Deal and Circular Economy, zero emissions by 2050 regarding the installed base is only achievable by forced replacement of switchgear with F-gas free technology. For the replacement high quality end-of-life handling is the key to minimize greenhouse gas emissions.

  Regulations for the decommissioning of SF6 equipment are in place but there is uncertainty of the actual implementation and little experience regarding the fractured private market. We expect leakage rates ranging from 1.5% (industry best practice) to 40% (private market worst case) with a best guess of 10% leakages in average during the whole end-of-life process. Reducing the average leakages from 10% to 5% will reduce the overall emissions by about 460 t SF6 or 40%.
  - The implementation of high quality lifetime management processes and monitoring Europe-wide is essential to minimize the impact of end-of-life leakages before starting forced replacement.
  - While we expect a well-established end-of-life management for utilities and bigger industries, incentives like credits for controlled decommissioning of SF6 equipment could be considered to reach the fractured private market.

1 Introduction

Fraunhofer Institute for Energy Economics and Energy System Technology IEE and Grenoble Ecole de Management (GEM) have performed a research study to investigate the impact of the application of the greenhouse gas sulfur hexafluoride (SF6) in power distribution grids. The work was performed between March 2019 and April 2020. Participation in the study was open to all electricity grid stakeholders.

The study analyzes the application of SF6 and of fluorinated gas (F-gas) free alternatives in medium voltage grids and intends to support the COP 21 Paris Agreement, and industry's sustainability commitments towards the nature and the planet. It comprises two parts:

- modeling of MV switchgear installation development under different boundaries showing the impact on SF6 emissions,
- survey and choice experiment to analyze market acceptance of SF6-free alternatives, as well as barriers and drivers to adoption.

This report describes the approach and the outcome of the first part of the study.

We designed an asset-based model in a bottom-up, grid topology oriented approach for Germany, France and Spain and extrapolated to the EU28 countries.

Using the model we were able to estimate the banked SF6 volume in MV switchgear for EU28 today with 8600 t and analyzed future scenarios.

The model allows investigating the impact and sensitivity of variable technical parameters (e.g. grid extension, technology market shares, switchgear lifetime) or changes in policy and regulation (e.g. forced replacement) from 2025 until 2050 with an outlook to 2100.

We present the main outcome of the analyzes.

2
Installed base of MV switchgear

There is no survey, register or public available data base of the actual installed MV switchgear and the used technology. The task was to come up with an approach to estimate the number of the installed MV switchgear today that also allows to investigate possible future developments considering different boundaries.

We designed an asset-based model in a bottom-up, grid topology oriented approach for Germany, France and Spain and extrapolated to the EU28 countries. The model allows investigating the impact and sensitivity of variable technical parameters (e.g. grid extension, technology market shares, switchgear lifetime) or changes in policy and regulation (e.g. forced replacement) from 2025 until 2050 with an outlook to 2100.

2.1 Model description

2.1.1 Considered grid topologies

The model is divided in three types of grid structures to be flexible in the adaptation of heterogeneous grid structures in different countries. Each type is again subdivided into different specific groups.

- The public grids are divided into three groups: urban, suburban and rural.
- The private grids contain two categories: compact and spacious facilities.
- Distributed Energy Resources (DER) grids cover wind farms, PV plants and storage systems.

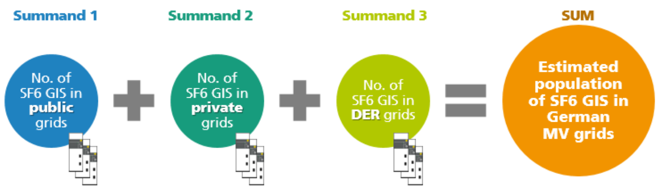


Figure 2: Overview of the used calculation method for the grid types

In Figure 2 an overview of the types and the used calculation method is shown. The estimated population of SF6 switchgear functional units is calculated by a summation of the grid types of public, private and DER.

The model allows the distinction between primary and secondary MV switchgear following typical grid topologies.

2.1.2 Age and lifetime and volume of the SF6 MV switchgear

We used an s-shaped curve starting in the 1970 and ending with the today's market penetration to model the market share per year. Today's market share of SF6 MV switchgear is assumed with around 45% in Germany, 65% in Spain and near 100% in France. In France mainly with AIS technology.
The model allows to choose the assumed average lifetime. We assume 60 years average lifetime meaning that there is no regular replacement done by now. Commercial lifetime usually is considered with 40 years but the market shows that the equipment is often operated for a longer period.

The volume and accordingly the SF6 mass used in the switchgear is considered for primary and secondary switchgear separately, can be adapted to the share of AIS / GIS technology and considers a reduction in the volume per functional unit around the year 2000.

2.1.3 Operation and end-of-life emissions

Operation emissions are set to 0.1% per year according to the relevant standards [1].

End-of-life emissions encompass the whole end-of-life handling from extraction via transport to recycling or deletion of the gas. Regulations regarding end-of-life handling are in place but the quality of the actual implementation is uncertain. The average end-of-life emissions are difficult to determine. Partly because of the different user groups and partly because there is only little experience in the market with the first equipment coming to the end of the regular lifetime.

Customers and operators of MV switchgear are on the one hand utilities and big industries. For this group we expect a lifetime management according to best practice approaches as described for instance in industry self-commitments like ZVEI in Germany. For utilities and big industry we assume end-of-life leakages with 1.5%.
On the other hand we have a high share of MV switchgear installations in the fractured private market from commercial buildings to smaller industry. For the private, fractured market we expect a variety ranging from a still good end-of-life management for bigger private companies to no end-of-life management at all.
Varying the share between the groups of users, in the private, fractured market with a range from good to no lifetime management came out with the following assumptions of the end-of-life leakages:

- industry best practice 1.5%,
- actual leakages best guess 10%,
- worst case 40%.

This wide range due to the existing uncertainty already highlights the need to establish a high quality monitoring system. The model allows to vary operation emissions as well as the end-of-life emissions. We show the impact later on.

Comparing operation emissions of 0.1% per year with end-of-life leakages we see that even for industry best practice end-of-life leakages are the equivalent of 15 years in operation. Therefor it is important to ensure high quality end-of-life handling Europe-wide, prior to all other measures.

2.2 Estimation of the installed base 2020

First, the general model was adapted to the grid structure in Germany, France and Spain. Second, the parameters of the countries Germany, Spain and France were merged to a model with one set of parameters that delivered the sum of the three countries and extrapolated with the relation of the electrical energy demand of Europe (EU28) in comparison with the three countries. For EU28 we estimate about 15 million MV switchgear function units of which 10 million use SF6 technology (GIS and AIS), see Table 2. Additionally, the table shows general data for the power consumption in EU28 used for the extrapolate the figures derived for Germany, France and Spain, as well as GHG emissions of the power generation, transmission and distribution industry in EU28 to see the potential impact of the banked volume of SF6 MV switchgear. The potential GHG effect of this banked volume is about 20% of the yearly GHG emissions of this industry sector.

Table 2: Modeling results for number of MV switchgear and SF6 banked volume and general data for model extrapolation and GHG impact

Modeled installed Base 2020	Germany	France	Spain	EU28 (extrapolation)
Number of MV switchgear functional units – total [million]	ca. 3,1	ca. 2,0	ca. 1,7	ca. 15
Number of MV switchgear functional units – SF6 [million]	ca. 1,4	ca. 2,0	ca. 1,1	ca. 10
SF6 banked volume in MV switchgear [t]	1300	1100	1200	8600 (196 million t CO2 equiv.)
General data				
Overall yearly electricity demand [TWh]	514	436	240	2700
Total GHG emissions (2017), CO2 equivalent [million t]	936	428	357	4483
Power generation GHG emissions (2018), CO2 equiv. [million t]				985 (196 → 20%)

2.3 Model validation

The results of the model were validated against public available grid data for Germany, Spain and France [2–4]. The resulting banked volume of SF6 were validated against the reported SF6 amount in the national inventory reports [5]. The model results for the actually installed base are in good accordance with both sources of public data.

3
Network extension development

The model allows to choose different network development paths for the specific grid types. We distinguished between the consumption grids (public and private grids in Figure 2) and the feed-in grids (DER grids in Figure 2).
For the consumption grids we considered a low grid extension scenario with an increase of the peak load by 5% between 2020 and 2035 and another 5% between 2035 and 2050. For the feed-in grids we chose the parameters in line with the expected increase in renewable energy installations to meet the political objectives towards carbon neutral energy production by 2035 and 2050, see Table 3.

	Germany Wind / PV [GW]	France Total [GW]	Spain Total [GW]
2018	59 / 46	25	28
2035	150 / 125	95	90
2050	180 / 250	140	160

Table 3: Development of wind and PV installations, model assumptions based on Fraunhofer scenarios[6-10] and international political objectives[3, 11-17]

Furthermore, we assumed that the necessary network development will be mainly accomplished by 2050. Under these boundaries we see an increase of MV switchgear functional units by about 42% until 2050. Renewable energy installations will account for the main share.

For a business-as-usual scenario with a steady share of today's technology, the banked volume of SF6 in MV switchgear will increase accordingly. The increase relative to the installed base in 2020 is shown in Figure 3. From 2050 we expect no significant network extension but show the unchanged value of 2100 just for comparison with the MV switchgear development scenarios later on.

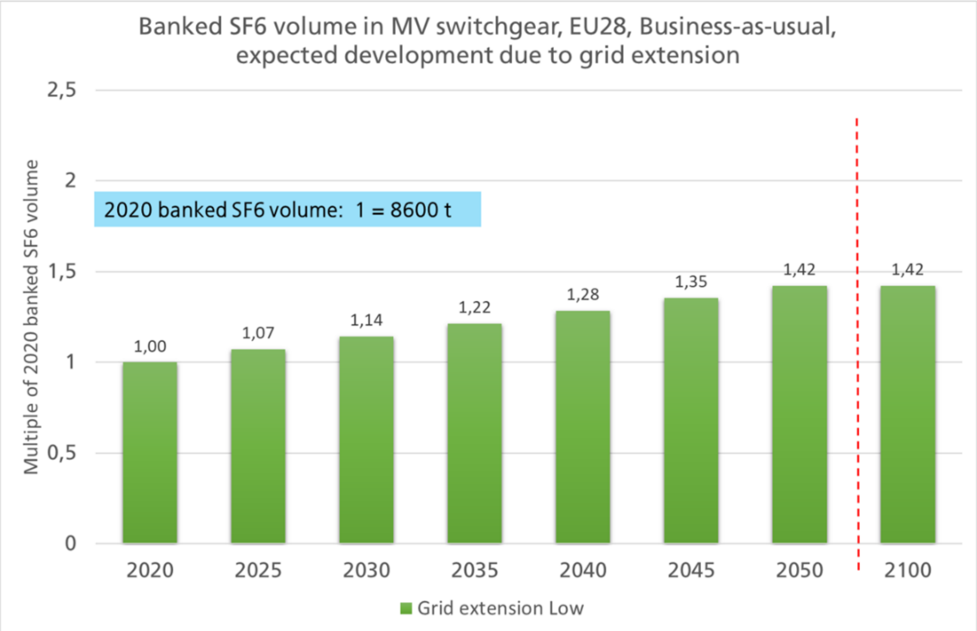


Figure 3: Banked SF6 volume, development for business-as-usual according to expected network extension in EU28

The operation emissions are directly correlated to the banked volume and will increase accordingly.

4
F-gas phase-down scenarios

We need to reduce the overall GHG emissions. Reduction of SF6 emissions is one building block. A variety of ways to phase down the use of SF6 in MV switchgear was analyzed. Three scenarios are presented in the following:

- business-as-usual scenario,
- replacement after lifetime,
- forced regular replacement.

All scenarios build on the estimated installed base for 2020 and the expected grid extension. Total SF6 emissions depend on the actual installed MV switchgear functional units for the operation emissions, and on the expected lifetime and lifetime management for the end-of-life leakages.

Business-as-usual scenario parameters

- New installations follow the market share of SF6 in 2020
- Operation emission 0.1%
- Replacement after an average lifetime of 60 years
- Replaced units follow the market share of SF6 in 2020
- Average end-of-life leakages 10% per decommissioned unit

Replacement after lifetime

- New installations follow between 2020 and 2025 the market share of SF6 in 2020
- Operation emission 0.1%
- Beginning in 2025 use of F-gas is banned for new and replaced installations
- Replacement after an average lifetime of 60 years
- Replaced units are F-gas free beginning in 2025
- Average end-of-life leakages 10% per decommissioned unit

European Green Deal

- New installations follow between 2020 and 2025 the market share of SF6 in 2020
- Operation emission 0.1%
- Beginning in 2025 use of F-gas is banned for new and replaced installations
- Forced regular replacement, linear yearly reduction of the installed base of the SF6 MV switchgear, total replacement until 2050
- Average end-of-life leakages 10% per decommissioned unit

The European Green Deal scenario is the only one where zero GHG emissions is reached until 2050. Forced replacement means replacement independent of the actual lifetime of the equipment. Beginning with the oldest equipment, of course, but SF6 MV switchgear installed in 2025 will be in operation only for 25 years.

The results for the different scenarios are presented as multiples of the banked volume and the emissions in 2020. Emissions of MV switchgear in 2020 are dominated by the operation emissions, because the expected number of decommissioned SF6 MV switchgear is negligible.

4.1 Banked volume

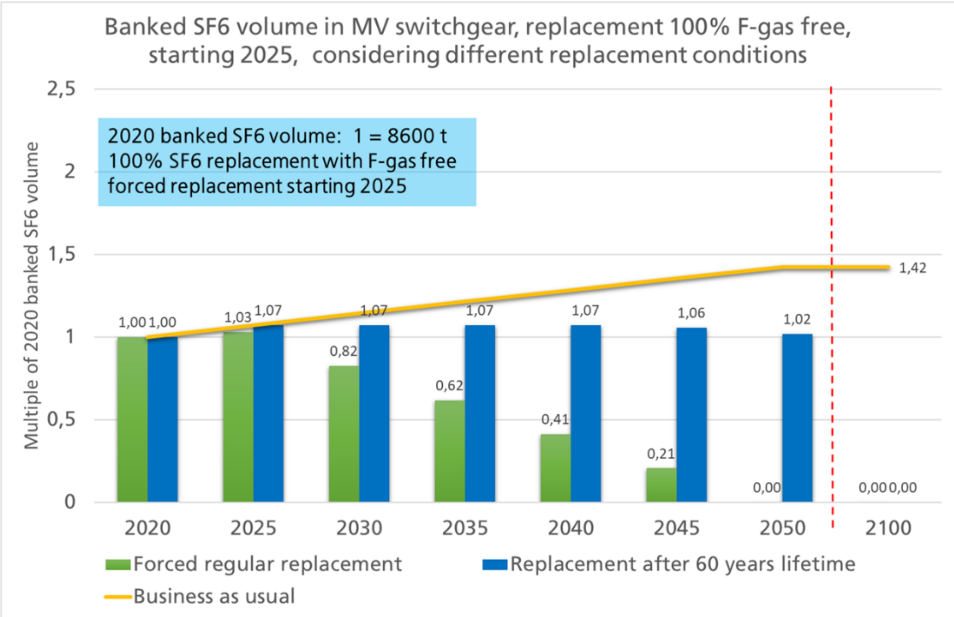


Figure 4: SF6 banked volume, development for business-as-usual, replacement after lifetime and forced regular replacement

For business-as-usual (yellow) the banked volume increases with the expected network extension. For the replacement after 60 years lifetime (blue) there is almost no effect until 2050, but until 2100 all SF6 MV switchgear will be decommissioned. Using the forced regular replacement (green) leads to total replacement until 2050. To achieve this about 400 thousand functional units have to be replaced per year. The number of new installations accounting for the expected network extension is about 160 thousand per year.

4.2 End-of-life emissions

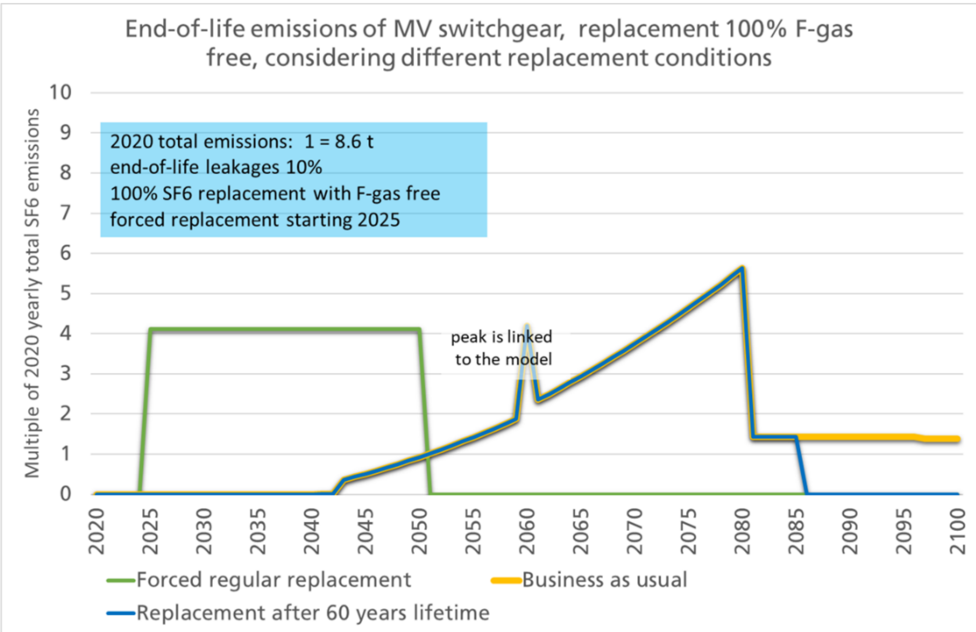


Figure 5: End-of-life leakages, development for business-as-usual according to expected network extension in EU28, average leakage 10% per decommissioned unit

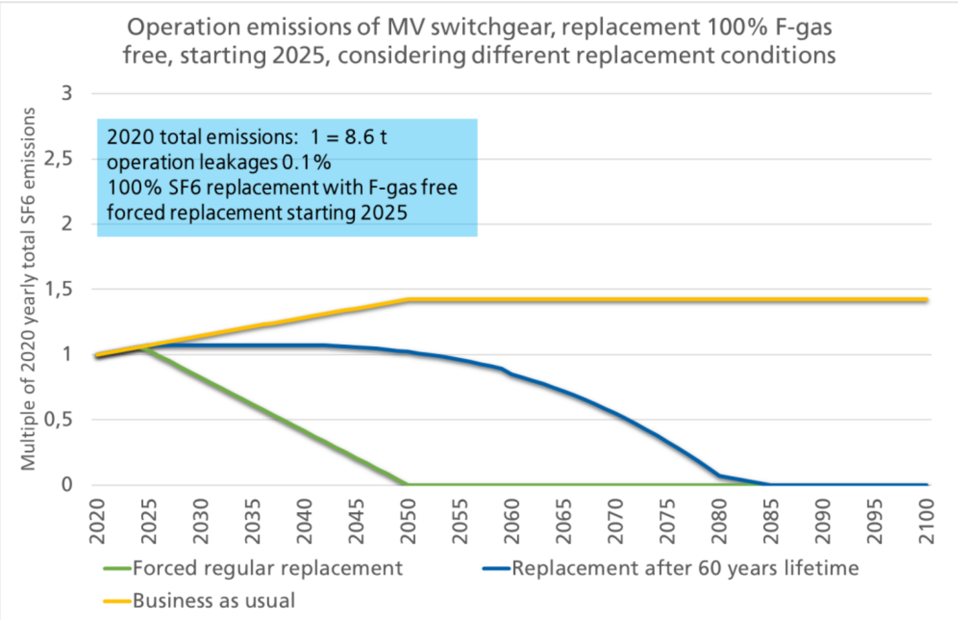
For business-as-usual (yellow) and replacement after lifetime (blue) end-of-life emissions will have no significant impact before 2040 under the assumption of an

average lifetime of 60 years. The increase for both mirrors the uptake in the market penetration of SF6 MV switchgear technology. The replacement after lifetime scenario shows a step in 2080 referring to the new installation between 2020 and 2025. Total replacement in this scenario will be achieved in 2085 following an assumed F-gas ban in 2025.
The steps and horizontal trend of the forced regular replacement (green) shows the steady number of decommissioned units per year between 2025 and 2050. The total amount of end-of-life emissions until 2085 is the same for replacement after lifetime and forced regular replacement, if no improvement is reached over the years for the end-f-life handling.

4.3 Operation emissions

Operation emissions are significantly lower compared to the expected end-of-life leakages. During a lifetime of 60 years the operation emissions are up to 6% of the banked volume (0.1% per year).
For all three scenarios the operation emissions follow directly the development of the banked volume, shown in Figure 6. Reducing the banked volume faster leads to overall lower operation emissions.

Figure 6: Operation emissions, development for business-as-usual according to expected network extension in EU28, 0.1% per year of banked



4.4 Total emissions

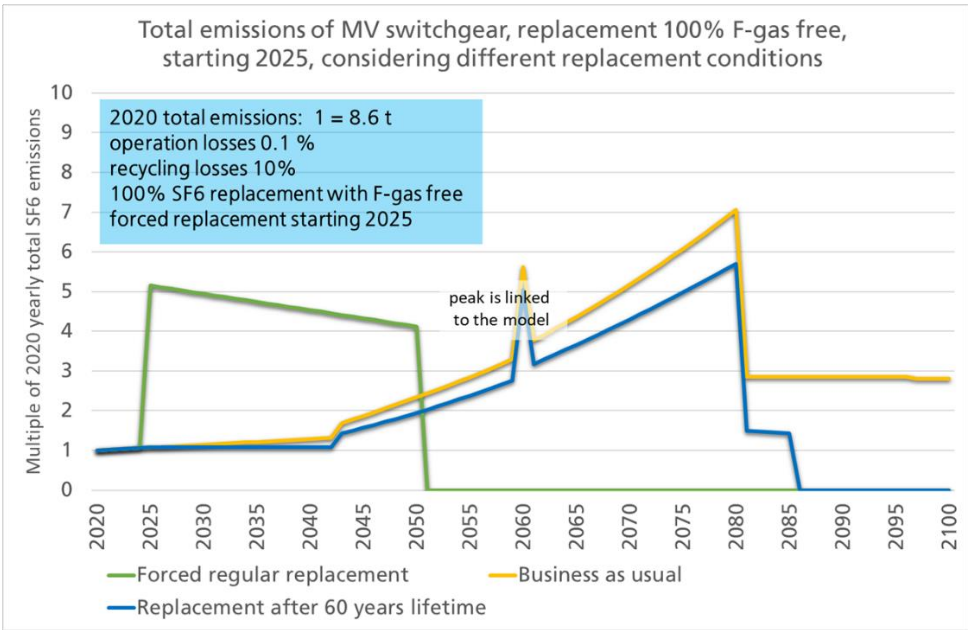


Figure 7: Total emissions, development for business-as-usual, replacement after lifetime and forced regular replacement, average leakage 10% per decommissioned unit, operation emissions 0.1% per year of banked volume

Total emissions are composed of operation emissions and end-of-life leakages. Zero GHG emissions until 2050 is achieved only by forced regular replacement (green). The spread between replacement after lifetime (blue) and business-as-usual (yellow) shows the impact of the assumed F-gas ban beginning in 2025 for new installations and replacement.

The accumulated emissions are shown in **Figure 8**.

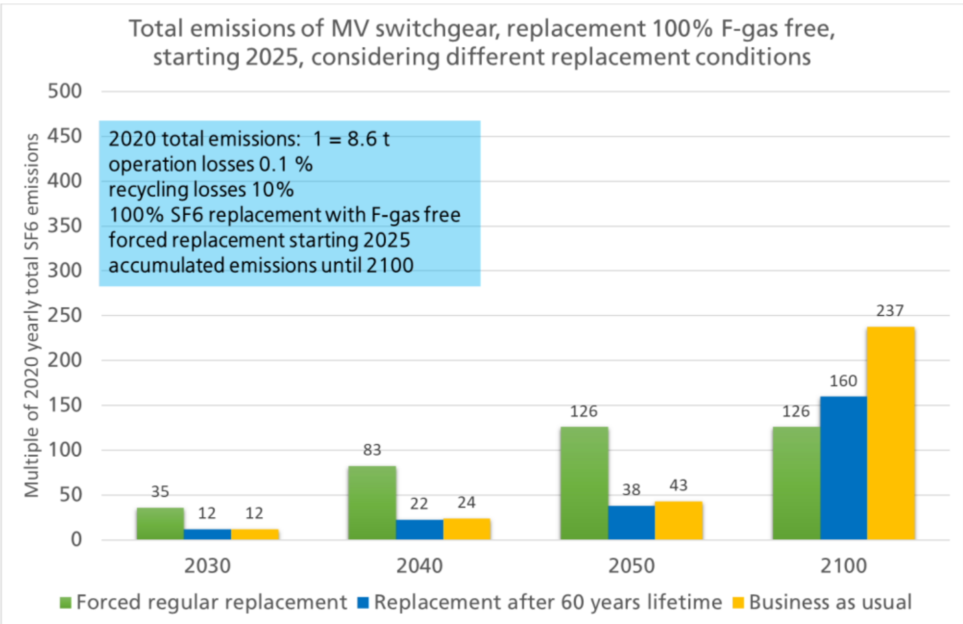
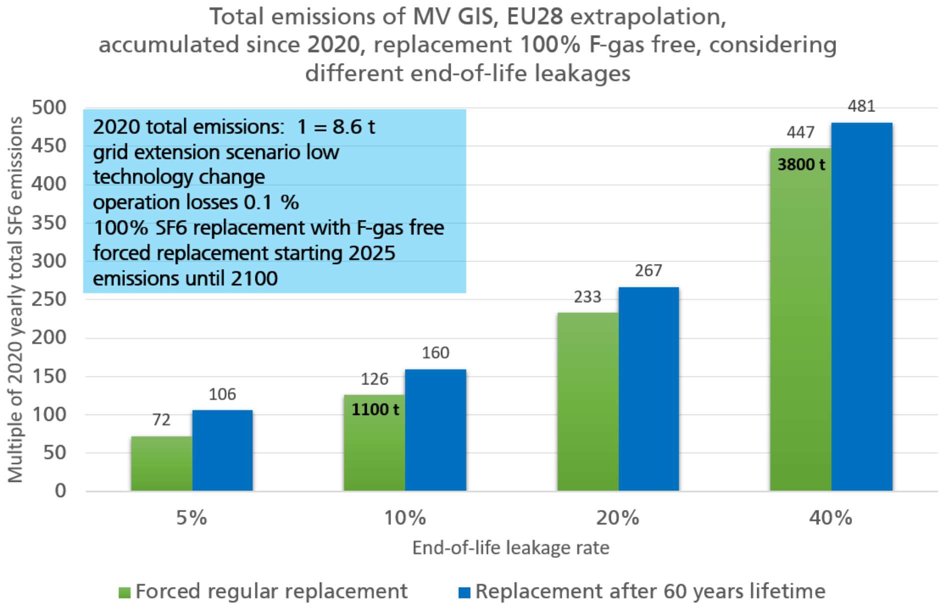


Figure 8: Total emissions, accumulated until 2100 for business-as-usual, replacement after lifetime and forced regular replacement, average leakage 10% per decommissioned unit, operation emissions 0.1% per year of banked volume

For the forced regular replacement (green) there is no increase of the total emissions after 2050 because all installations are replaced by 2050. The lower value in 2100 compared to replacement after lifetime (blue) is due to lower operational emission because of faster replacement. For business-as-usual (yellow) accumulated emissions will further increase beyond 2100.

Finally, the impact of different qualities of the end-of-life handling is shown.

Figure 9: Total emissions, accumulated until 2100 for replacement after lifetime and forced regular replacement, different average leakage per decommissioned unit, operation emissions 0.1% per year of banked volume



Our best guess for the end-of-life leakages is 10%. But there is a high uncertainty. The expected worst case for the forced regular replacement (green) more than triples the accumulated emissions. An average of 5% instead of 10% end-of-life leakages would reduce the accumulated emissions by about 40% showing the importance of the implementation of a good monitoring of the end-of-life process.

5
Conclusions and recommendations

Three main drivers define the development of SF6 emissions in medium voltage switchgear:

- network extensions,
- operation emissions, and
- end-of-life handling.

The end-of-life handling has the key role. Network extension effects are also significant.

We expect network extensions due to demand increase but mainly due to the increase in renewable energy installations leading to an increase of about 40% in MV switchgear installations until 2050. Provided a steady market share of SF6 applications this leads to the same increase of the banked SF6 volume and yearly operation emissions.
We recommend starting as soon as possible using F-gas free equipment wherever applicable to minimize network extension effects on greenhouse gas emissions.

Considering the European Green Deal and Circular Economy, zero emissions by 2050 regarding the installed base is only achievable by forced replacement of switchgear with F-gas free technology. For the replacement high quality end-of-life handling is the key to minimize greenhouse gas emissions. Regulations for the decommissioning of SF6 equipment are in place but there is uncertainty of the actual implementation and little experience regarding the fractured private market.
We expect leakage rates ranging from 1.5% (industry best practice) to 40% (private market worst case) with a best guess of 10% leakages in average during the whole end-of-life process.

Reducing the average leakages from 10% to 5% will reduce the overall emissions by about 460 t SF6 or 40%. The implementation of high quality lifetime management processes and monitoring Europe-wide is essential to minimize the impact of end-of-life leakages before starting forced replacement.
While we expect a well-established end-of-life management for utilities and bigger industries, incentives like credits for controlled decommissioning of SF6 equipment could be considered to reach the fractured private market.

6 Abbreviations

AIS	Air insulated switchgear
COP 21	2015 United Nations Climate Change Conference, Conference of parties 21
DER	Distributed Energy Resources
ENA	Energy networks association
EU28	European Union member states until January 2020
F-gas	Fluorinated gas
GEM	Grenoble Ecole de Management
GHG	Greenhouse gas
GIS	Gas insulated switchgear
MV	Medium voltage
SF6	sulfur hexafluoride
UK	United Kingdom
ZVEI	Zentralverband Elektrotechnik- und Elektronikindustrie e.V.

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8
Contact and project background

8.1 Contact

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8.2 Project background

"F-gas free" is a research initiative on SF6 and F-gas free alternatives for medium voltage (MV) gas-insulated switchgear installations in Europe. Project duration: 03/2019 - 04/2020. Initial sponsors: Siemens, Schneider electric. Project announcement and invitation to participate was done via the website, press information and via direct contact to manufacturers during Hannover fair 2019 and to associations like T&D Europe, ZVEI in Germany and ENA in UK.

The study is intended to support the COP 21 Paris Agreement, and industry's sustainability commitments towards the reduction of greenhouse gas emissions. The F-gas team of the European commission and consultants working on the input for the coming update of the F-gas regulation were informed about preliminary results and the overall outcome of this study.

Project description and main outcomes are publicly available via the project website: www.f-gas-free.eu

8.2.1 Short profile Fraunhofer IEE

The **Fraunhofer Institute for Energy Economics and Energy System Technology IEE** in Kassel researches for the national and international transformation of energy supply systems.
We develop solutions for technical and economic challenges in order to further reduce the costs of renewable energies, to secure the supply despite volatile generation, to ensure grid stability at the usual high level and to make the business model of the energy transition a success.
With the help of our scientific, technical and operational offerings and solutions, we support our customers and partners from politics and industry.