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STUDY OF THE LIFE CYCLE OF GAS-INSULATED MEDIUM-VOLTAGE SWITCHGEAR.

Cost factor analysis of F-gas containing and F-gas free switchgear over their life cycle.

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Summary

The Fraunhofer Institute for Energy Economics and Energy System Technology IEE has conducted a study to investigate the cost factors in the life cycle of medium-voltage switchgear. The focus of this study is on the time range from procurement to disposal of gas-insulated switchgear (GIS) with insulating gases containing fluorine gas as well as fluorine gas-free insulating gases. The study was conducted between February 2021 and March 2022.

In the study, the costs of a medium-voltage switchgear with an average number of switchgear panels in German public power networks during the life cycle as well as the environmental impacts due to the different insulating gases or system types used are considered. The costs were determined for this exemplary hypothetical switchgear system with an average number of switch panels in common public supply networks. The aim is to compare market factors and environmental impacts.

The parameters included in the cost factors are changed within the observation period in order to capture their influence or share in the total costs.
For the calculation of the life cycle costs, the LCC-CO2 tool from the project SMART SPP - innovation through sustainable procurement was adapted and used with regard to the observation period and the CO_2 certificate price consideration.

The calculations are based on values from literature research and expert interviews among stakeholders on various aspects of the life cycle phases of planning, operation and disposal of switchgear.

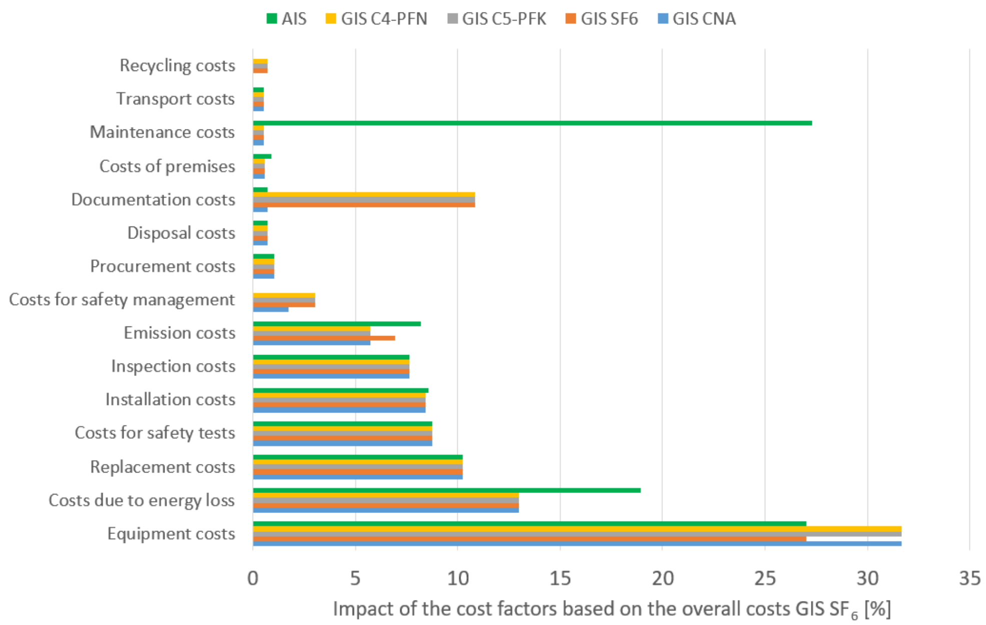


Figure 1: Overall costs of the switchgear for the technologies considered over an observation period of 40 years. Overall costs GIS SF_6 as basis (100%).
GIS - gas-insulated switchgear
AIS - air-insulated switchgear
SF_6 - sulfur hexafluoride
CNA - Components of Natural Air
C5-PFK - perfluoroketone
C4-PFN - perfluoronitrile

For C5-PFK and C4-PFN, the documentation requirements have been taken into account in accordance with SF_6 due to the fluorine gas content.

The study found a difference in cost of -8.7% to 4.4% between the gas-insulated switchgear types, depending on the period considered, for the same lifetime. These differences result from the switchgear system costs, the emission costs, the documentation costs and the costs for the safety management for insulating gases as well as for the recycling of insulating gases. The lowest total cost is for the GIS with Components of Natural Air (CNA) as the insulating gas.

The air-insulated switchgear (AIS) is approx. 18.9% to approx. 20.5% more expensive than the gas-insulated solution with SF_6, depending on the selected observation period and the considered equal service life. These additional costs result from the categories of operation, plant inspection and CO_2 costs. The main drivers are the costs due to energy loss (electricity price), the emission costs from electrical losses (CO_2 equivalents of the electricity mix) and the costs for the maintenance of the switchgear.
A ranking of the identified cost drivers was established based on calculated reference values.

The emissions in CO_2 equivalents are considered as emissions from the electrical losses and the leakage of insulating gases. For the switchgear under consideration, the emissions from electrical losses are dominant for the current electricity mix in Germany.

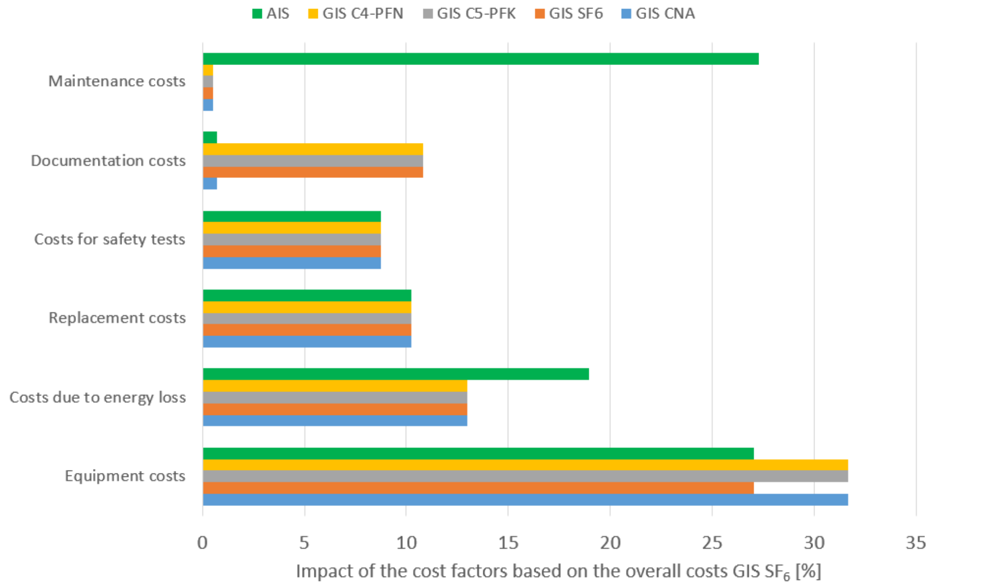


Figure 2: Cost factors affecting the area of equipment testing.

GIS - gas-insulated switchgear
AIS - air-insulated switchgear
SF_6 - sulfur hexafluoride
CNA - components of natural air
C5-PFK - perfluoroketone
C4-PFN - perfluoronitrile

For C5-PFK and C4-PFN, documentation requirements were considered in accordance with SF_6 due to the fluorine gas content.

The costs of equipment, maintenance, energy loss, replacement, safety tests and documentation have been identified as cost factors that account for a large proportion of the total costs. The costs for documentation are low for switchgears without fluorinated gases. For the alternative fluorinated gases, documentation requirements corresponding to SF_6 have been assumed, but the legal requirements are currently interpreted differently. In the next few years, these may be clearly defined or changed. Maintenance is decisive for the cost difference between air-insulated and gas-insulated switchgear.

1 Introduction

1.1 Objective

Within the scope of a scientific study, the life cycle of medium-voltage switchgear with fluorine-containing insulating gas (F-gas) and fluorine-free insulating gas (F-gas-free) was analyzed, considering the stages from acquisition, installation and operation to the end of their service life.
The main factors, processes and obligations that are required in the use of the switchgear and have an influence on costs (CAPEX (capital expenditure) and OPEX (operating expenditure)) were recorded in all life phases. In addition to acquisition, these include factors such as maintenance, replacement, space requirements, training or disposal. Gas-insulated switchgear (GIS) using fluorine gas-free solutions was compared with functionally equivalent solutions using SF_6 or alternative fluorinated gases or gas mixtures, as insulating gas.
Air-insulated switchgear (AIS) was also included in the comparative analysis. Effort and cost to the switchgear operator during the specified life cycle were analyzed and compared for the different technologies.

Significant differences between F-gas-free GIS and those with F-gases (including SF_6) were quantified. In particular, the investment costs for the switchgear as well as other required equipment, materials and services and the required costs for proper installation, operation and maintenance as well as disposal at the end of life were considered.

1.2 Implementation

The study was conducted between February 2021 and March 2022.

1.2.1 Basis for comparison

The focus of this study was on the time from procurement to disposal of GIS with insulating gases containing F-gas as well as F-gas-free insulating gases. For the GIS, sulfur hexafluoride (SF_6), as well as gas mixtures with perfluoroketone (C5-PFK) and perfluoronitrile (C4-PFN) and gas mixtures exclusively from components of the natural ambient air "Components of Natural Air" (CNA: N_2, O_2, CO_2) were considered.

In order to provide a basis for comparison, this study defined a hypothetical "average switchgear", executed in the different technologies and for which the different parameters were varied.
Based on the data for the urban distribution network of the LCA study [1], a hypothetical switchgear is defined with proportions of primary as well as secondary distribution level switchgear.
For the supplied network area, 23 primary switchgear panels are specified and 132 ring-main-unit (RMU) switchgear panels.
This ratio is used to calculate the data for the hypothetical switchyard. It consists of 85% of ring main units - RMU (with 3-panels, secondary units) values and 15% primary units (one functional unit/ panel). The hypothetical switchgear has calculated 3.17 panels, which is roughly the ratio between the panels in the network [1] and the number of switchgear systems. Based on market data and studies [1, 2], this switchgear represents an average of switchgears for primary and secondary units for

the distribution levels used in public utilities. According to the information from the expert interviews, this division is more suitable for public grids than for industrial grids, where divisions with predominantly primary switchgear may also occur.
For the input parameters of the hypothetical switchgear, averaged values for the purchase price, the energy loss, the spatial volume and the CO_2 emissions during production and at the end of life were taken into account.

1.2.2 Method

The study uses an adapted life cycle cost and CO_2 calculation tool to consider the multitude of relevant factors. First, cost factors are identified through literature research and expert interviews. The identified cost factors are varied over the observation period to determine the sensitivity of individual cost factors.

The production of the equipment provides a fixed cost contribution, which is presented as an input parameter but is not further detailed in the study. In addition to data from manufacturers, the EU Commission report on alternatives to fluorinated greenhouse gases in switchgear [3] was considered for switchgear costs with alternative insulating gases.

The study primarily uses data for Germany as the application area. For some cost factors (e.g. energy price (electricity) or the emission factor electricity mix), values available in the literature for other European countries were used to extend the scope of the study.

In view of a future development to regulate environmental pollution more strongly and to charge it financially, the environmental friendliness during the operating time and the possibilities of an environmentally friendly disposal play an increasing role in addition to the purely economic considerations in the procurement of the switchgear. Based on this assumption, fluorine-containing insulating gases are recycled in this study and the CO_2 equivalents of the insulating gases are compared when they are released.

1.2.3 LCA-Tool

In this study, a freely available LCA tool is used for the life cycle analysis. The Excel-based LCC-CO2 tool is published by ICLEI - Local Governments for Sustainability and was developed in the EU project SMART SPP [4] (https://www.smart-spp.eu).

The tool is used to determine and compare the costs and the carbon footprint of different products and services over a defined period of time. The focus of the development was on the support of public tenders. The goal is to support the introduction of new products with a more favorable CO_2 balance. For this purpose, in addition to the costs in euros, the emissions in CO_2 equivalents are also output directly.

In the tool, data on prices, losses, maintenance costs, service life, etc. are recorded for the products under consideration and offset against each other in the calculation sheets. Individual points can be considered in more detail, provided that the corresponding data are available. For example, different energy sources can be taken into account for the calculation of emissions, and the corresponding electricity mix can be selected. For different energy sources and the electricity mix of different EU countries, data from GEMIS 4.5 are already available.

The tool divides the calculated costs into the following areas:

- Acquisition
- Operation
- Plant inspections
- CO_2-costs
- End of life

For this study, the tool has been adapted and extended with the permission and approval of the publisher.
Due to the adjustments made, the observation period for long-life products, such as switchgear, has been extended to 60 years in order to be able to consider more than one full life cycle, in this study 40 years. The values of the emission factors for the electricity mix of the different EU countries were updated. For the consideration of the prices for CO_2 certificates, different scenarios are predefined in order to take into account the current dynamic discussions [5–9] about the price development for CO_2 certificates and to consider at least a wide spectrum of the current discussions.

The predefined scenarios are:

- Scenario "stable"
  - Costs remain in the range of 55 -65 € / t CO_2 after 2025.
- Scenario "gradual"
  - Slow development of costs up to 82€ / t CO_2 in 2080.
- Scenario "moderate"
  - Increase in costs after 2025 by 2€ / t CO_2 per year.
- Scenario "intense "
  - Increase in costs after 2025 by 5€ / t CO_2 per year.
- Scenario "Impact compensation"
  - Cost increase to 350€ / t CO_2 by 2040.

This is intended to enable a rapid comparison of different environmental policy developments [5–9]. For the study, the scenario with a moderate increase in the price of CO_2 certificates after 2025 is used to determine the reference value.

In this study, a life cycle of the switchgear ends with the expected lifetime due to aging and wear. Accordingly, the tasks can no longer be performed safely; an earlier replacement with disposal of the switchgear is not considered in this study.

2
Lifecycle cost factors

There are parameters in the life cycle of medium-voltage switchgear that have different effects and influence each other. To simplify the model, the parameters are related to the user of the equipment and the period between procurement and disposal of the equipment is considered.

The process of production results in a preload, which is recorded as a fixed value. This affects the overall balance and can be partially offset by recycling. Different manufacturers use different sources for raw materials and energy procurement, which means that the data are not directly comparable. Additionally, these sources and thus their contribution can change. Some of the switchgear types considered are mainly produced by individual manufacturers. Therefore, a value for CO_2 equivalents is considered for production, regardless of the switchgear type; the detailed manufacturing processes are not examined in this study.

Disposal is also included as a fixed value, as this process is often carried out by external companies at fixed prices, cost factors are calculated using these fixed prices. The disposal of the switchgear, includes the removal as well as the dismantling of the equipment and placement of the components in the recycling cycle or in the residual waste or hazardous waste. The recycling process includes the extraction and recycling of the insulating gases. A detailed consideration of the processes "disposal" and "recycling" of the insulating gases with possible variations is not part of this study.

In the following, it is further assumed that insulating gases containing fluorine are recycled and not incinerated or released uncontrolled into the environment. This improves the environmental balance, at a comparatively low cost per kilogram. Possible reuse of recycled gases and higher prices for CO_2 certificates in the future support this assumption, as the combustion of SF_6 is energy-intensive. Other harmful decomposition products that may be generated during operation are assumed not to be released in this approach [10, 11].
Especially the harmful properties of alternative insulating gases containing fluorine gas, directly or in the form of decomposition products due to electric arcs, as stated in [10], suggest a future tightening of the documentation obligation in the course of environmental and climate protection, which extends to all insulating gases containing fluorine gas. A corresponding tightening has been assumed for all F-gases in this study and thus documentation requirements are applied that correspond to those for the insulating gas SF_6.

The inflation rate and productivity measures were not taken into account. Also for the energy price (electricity reference value 10.61 ct/kWh) no price increase was taken into account.

Experts Interviews

To determine the range for the parameters, expert interviews were conducted in addition to the literature research. These interviews provided greater insight into the areas of operations, planning, and disposal and supported or supplemented the literature review. Participating experts were from the fields of:

- Public network operators,
- Private network operators,
- Disposal companies,
- Planners for electrical installations,
- Companies for electrical installations.

At this point, we would like to thank the participants for answering the questions.
The expert interviews revealed that the various network operators handle some cost factors differently. In particular, there were significant differences in procurement costs, inspection and maintenance costs. Cycles for inspection and maintenance also vary greatly from one operator to another and are due not least to different experiences and operating conditions.
It can also be seen that with an increasing number of switchgear panels and RMUs, the specific costs become lower; this was particularly evident in the data on procurement costs and safety management for insulating gases. Here, a different personnel key for employees per RMU or per primary switchgear panel and the use of standard solutions instead of individual configurations is evident. Public utility networks can include several hundred switchgears, while industrial networks often include fewer than 50 units.
There is a common understanding on the electrical losses of switchgear panels and RMUs, these are usually not considered separately by operators, as exact data on this are not known and equipment such as transformers and cables cause greater losses, thus the switchgear losses are considered to belong to this equipment.

It is also noticeable that although GIS is designed to be maintenance-free, network operators also perform maintenance on this equipment in order to minimize fault and malfunction risks to the best of their ability.

For this study, the parameters of safety testing, inspection and maintenance are composed as follows in terms of work:

- Safety testing includes the costs of switchgear that are incurred for testing the proper condition and electrical safety as well as the protective functions in accordance with applicable regulations and ordinances (e.g. DGUV V3, VDE AR-N 4110). The costs are calculated on the basis of annual amounts, even if the inspections are carried out in cycles specific to the network operator, in some cases over several years.
- Inspection according to DIN 31051 [12] or visual inspection of the switchgear.
- Maintenance includes work such as mechanical and electrical function checks, determination of switching times, checking and lubricating drives, checking or renewing corrosion protection, checking and retightening connections.

In practice, such work is also carried out, as far as possible, on GIS.
Furthermore, the downtimes of a switchgear represented a special case. For cyclical measures such as maintenance and inspection, costs are often only incurred for the replacement supply or the switchover to a redundant system and are therefore not always recorded as separate costs. In public networks, a penalty may be applied by the network regulating authority (in Germany: Bundesnetzagentur).

In industrial networks in particular, the specific outage costs for switchgear panels can be in the 5 to 6 digit range per hour.

Contrary to the empirical values from [1], the service life of AIS was seen by the experts as at least equal to the service life of GIS.
A possible retrofit to increase the service life or a shortening of the service life due to damage is not considered in the study.

Components and switchgear panels that are still fully functional are kept in reserve, but since this depends on the individual components, no general residual value or reuse is taken into account in practice.

2.1 Cost factors and input parameters

Cost factors include costs incurred to acquire, operate, and dispose of the switchgear. The observation period begins with the transfer of ownership from the manufacturer to the operator.

The disposal process is divided into sub-steps of replacement or dismantling, disposal and recycling of the fluorine-containing insulating gases.

2.1.1 Calculation of the cost factors

The following cost factors were considered:

1. Equipment costs
2. Procurement costs
3. Documentation costs
4. Emission costs (gas leakage and emissions from lost energy)
5. Disposal costs
6. Installation costs
7. Inspection costs
8. Costs due to energy loss
9. Replacement costs
10. Costs Downtime safety tests
11. Downtime maintenance costs
12. Costs of premises
13. Costs of safety management
14. Costs of safety tests
15. Recycling costs
16. Transport costs
17. Maintenance costs

2.1.1 Parameters for cost factors in the life cycle of the switchgear

The various parameters included in the cost calculation are categorized according to their occurrence.

- Annual
  Parameters of the category "annual", make an annual contribution to the calculation.

- Once in the life cycle
  Parameters of the category "once in the life cycle", contribute once in the life cycle of a switchgear.

- Special condition
  Parameters of the category "special condition", contribute in case of special conditions, which can neither be categorized as "annual", nor as "once in a life cycle".

- Varied parameter
  Parameters of the category "varied parameter", have been varied for the calculation of the cost factors.

- Fixed parameter
  Parameters of the category "fixed parameter", are assumed to be constant for the calculation of cost factors.

The parameters considered for the calculation of cost factors are:

Labor costs [€/h] – special condition, fixed parameter.

- Costs incurred for one working hour. These costs are multiplied by the time required for the cost factors procurement, documentation obligations, inspection as well as safety management for insulating gases.

- According to the interviews, some tasks, such as the installation of a switchgear, are contracted out to outside companies with a fixed price or separate costs for a labor hour. Accordingly, labor costs are not applied to all cost factors.

Replacement/Dismantling [€] – once in the life cycle, varied parameter.

- Cost of replacing or dismantling the switchgear at the end of the life cycle. In this study, no distinction is made between replacement and dismantling. As with the installation parameter, the costs are used directly.

Provision of premises [€] – special condition, varied parameter.

- Costs for the provision of the premises. To determine this, the required enclosed space is taken into account based on the costs of a warehouse. A possibly necessary concrete body for enclosure is not considered. The size of the GIS switchgear has been assumed to be the same for all insulating gases, corresponding to available SF_6 equipment. For the size of the AIS, the dimensions of available switchgears were used.

Procurement [h] – once in the life cycle, varied parameter

- The amount of time spent on activities related to the procurement of a switchgear. This includes planning, obtaining and checking quotations, organizing the processes up to installation of the equipment. The corresponding time spent on work is varied under this parameter.

CO_2-equivalents from gas emissions [kg] – special condition, fixed parameter

- The CO_2-equivalents from gas emissions represent the emissions of the insulating gas during operation in the observation period, as well as the emissions during extraction for recycling. The climate impact of the respective gases or gas mixtures is taken into account and shown as the corresponding mass of CO_2 equivalents.

CO_2-equivalents from energy loss [€/kg] – special condition, varied parameter

- The CO_2-equivalents from energy loss represent the climate-impacting emissions caused by power losses during operation in the observation period. For this purpose, the loss energy is multiplied by the emission factor assigned to a specific electricity mix.

CO_2-certifikates [€/kg] – special condition, varied parameter

- Costs for offsetting climate-impacting gas emissions. The price of CO_{2-} certificates for compensation corresponds to the average value of a possible price development.

Documentation obligation [h] – annual, varied parameter

- Documentation obligation, or documentation for short, includes the recording (documentation recording) of the switchgear and any insulating gas quantities in its own system, as well as the reporting (documentation reporting) of the fluorine gas quantities to appropriate public bodies. In this study, the time required to record the switchgear during commissioning and the annual reporting of the fluorine gas quantities are considered.
- In this study, the insulating gases containing fluorine gas are treated in the same way with regard to the documentation obligation.

Downtime losses [€/h] – annual, varied parameter

- The downtime losses represent the financial expenses to compensate for the planned unavailability or the penalty by the Federal Network Agency mentioned in the expert interviews.
- It is assumed that the switchgear does not generate any losses (e.g. due to production downtime) in the event of planned unavailability due to redundancy and organizational arrangements.

Downtime safety tests [h] – annual, fixed parameter

- Downtime safety test includes the downtime for the planned unavailability of the switchgear, during which safety tests, such as the recurring test of stationary electrical systems according to DGUV V3 and protection tests according to VDE-AR-N 4110 [13], are carried out on the switchgear, as well as the necessary preparation and follow-up times.

Downtime maintenance [h] – annual, fixed parameter.

- Downtime maintenance includes the downtime, for the planned unavailability of the switchgear, in which the switchgear is maintained.

Electricity mix emission factor [kg/kWh] – special condition, varied parameter.

- The emission factor for the provision of electrical energy, indicates how many kg of CO_2 are produced in the provision of 1 kWh according to the electricity mix.

Energy price (electricity) [€/kWh] – special condition, varied parameter.

- Cost incurred for the purchase of electricity per kWh.

Disposal [€] – special condition, varied parameter

- Cost of disposing of the old switchgear equipment. Disassembly into recyclable materials and disposal of non-recyclable components.

Inspection [h] – annual, varied parameter

- Time required for inspection according to DIN 31051 [12] or visual inspection of the switchgear.
- Due to the different conditions of different operators, it is assumed that the switchgear system is located in a short distance, which is reached without travel times and corresponding costs and emissions. Accordingly, for operators with widely distributed switchgear systems, it can be assumed that the inspection is performed in connection with other activities, such as switching operations, which means that no additional travel is required for the inspection.

Installation [€] – once in the life cycle, varied parameter.

- Costs for installation and commissioning of the switchgear. External companies are often used for this. As a result, this parameter flows directly as a cost into the installation costs.

Purchase price [€] – once in the life cycle, fixed parameter

- The purchase price represents the price for which the equipment is purchased from the manufacturer.

Recycling of fluorine gases [€] – once in the life cycle, varied parameter.

- Cost of extracting the fluorine-containing insulating gas to prepare it for reuse at the end of the switchgear's life.

Safety management for insulating gases [h] – annually, varied parameter.

- In this study, safety management for insulating gases, or safety management for short, refers to the time required to train employees in the handling of insulating gases.

Safety tests [€] – annual, varied parameter

- Safety tests includes the costs of the switchgear that are spent on testing the proper condition and electrical safety as well as the protective functions in accordance with applicable regulations and ordinances (e.g. DGUV V3, VDE AR-N 4110). The costs are calculated on annual amounts, even if the tests are carried out in a cycle of maximum 4 years.

Transport [€] – once in the life cycle, varied parameter

- Cost of transporting the equipment from the manufacturer to the place of installation.

Energy loss [kWh] – annually, varied parameter

- The energy loss is calculated for the assumption of a continuous load with an operating current corresponding to 50% of the rated switchgear current.

Maintenance [€] – annual, varied parameter

- Costs incurred for direct maintenance work as well as cleaning of the switchgear.

Costs for possible storage of spare equipment or spare parts are not considered in this study.

2.1.1 Obtaining the cost factors from the parameters

The cost factors are composed of the various parameters, as shown in Figure 3.

In the illustration are:
Cost factors;
Blue boxes with white writing,

Parameters;
blue framed boxes with black writing.

Subsets;
green framed boxes with black writing.

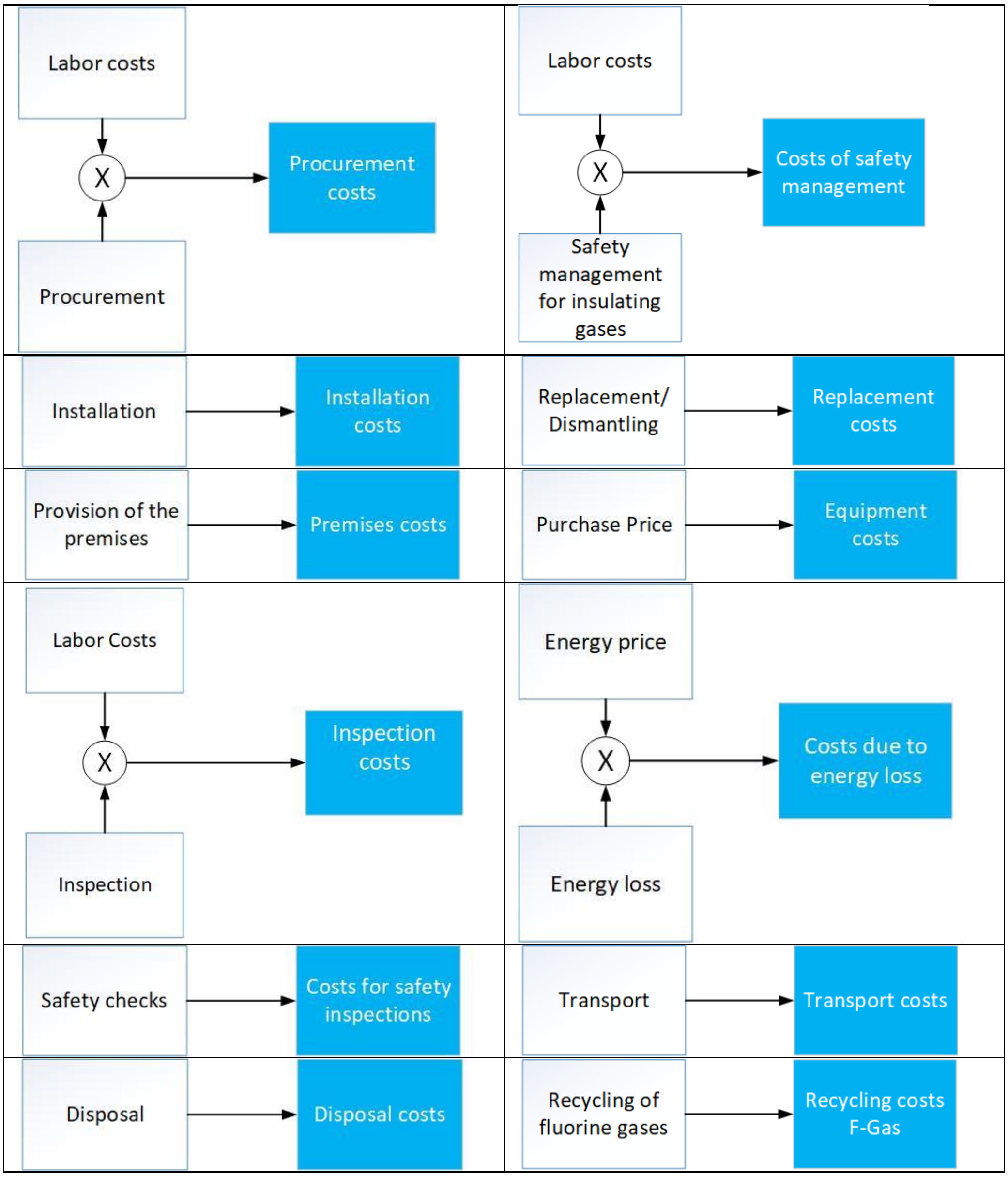
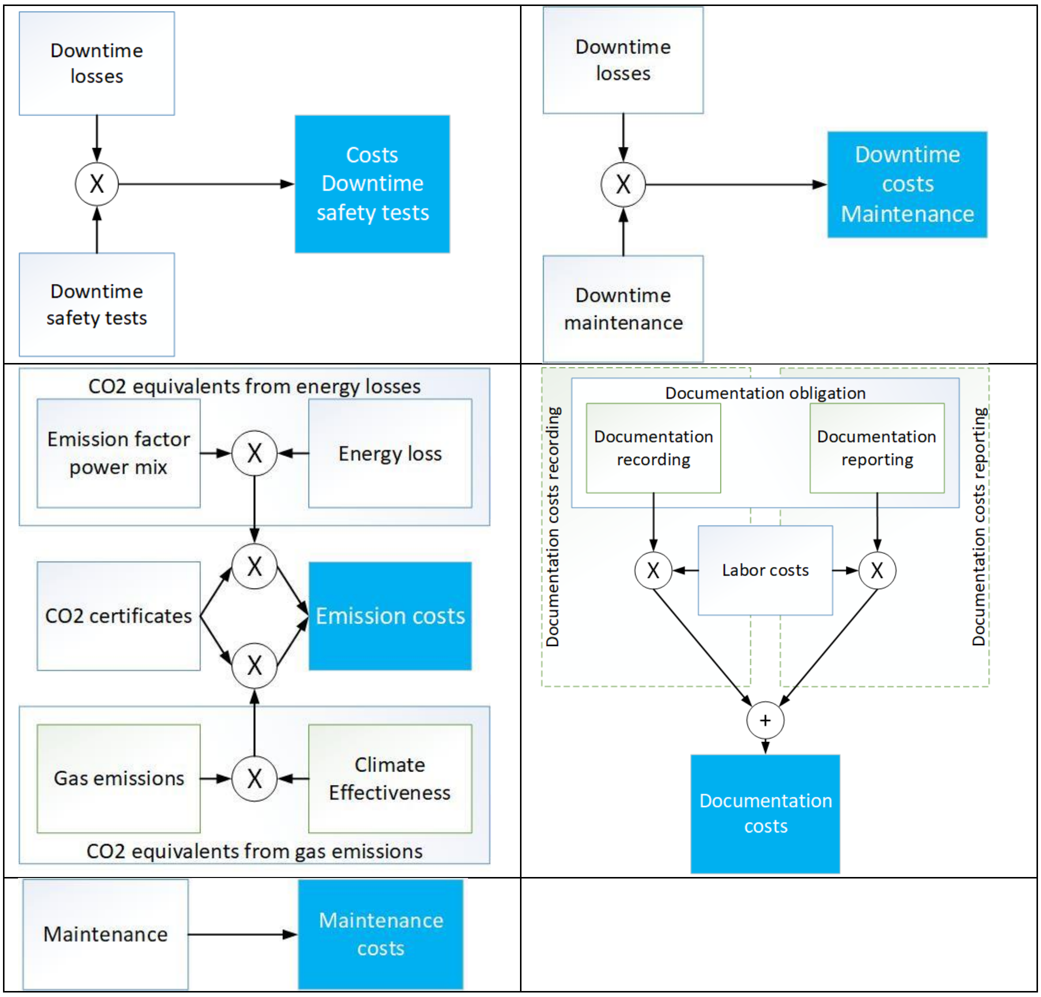


Figure 3: Composition of the individual cost factors from the parameters and subsets.



Subsets are quantities from which some of the parameters are calculated. Their representation serves for a better understanding of what has been considered for the corresponding parameters and cost factors. Some of the parameters and subsets are added or multiplied according to the representation, while other parameters directly yield the cost factors.

2.1.1 Determined range of parameters

The range of parameters was determined on the basis of literature research and expert interviews with planners, operators and disposers of switchgear and its insulating gases, and presented in Table 1. Based on the results, the parameters were divided into 3 categories.

The categories are based on when the corresponding costs/expenses are incurred, as:

- annual amount,
- once in the lifetime or
- under special conditions.

The corresponding reference value is given in square brackets. The reference value is an average value calculated by weighting the specified values for the determined range of the individual parameters. Some factors are given separately for GIS or AIS and F-gas containing or F-gas free.

For the emission factor, the sources [14–16] were used and an average value for Germany was assumed as a reference. The range was taken from today's fluctuations, with individual extreme values being neglected. The European situation is considered separately after the sensitivity analysis.

The information in the study [1] and the expert interviews serve as the basis for the service life specifications. Manufacturers' specifications often refer to a safe service life of 30 to 40 years. Experience shows that medium-voltage switchgear can also remain in service for longer than the lifetimes assumed in this study [2]. Long-term experience is not yet available for switchgears using the new insulating gases containing fluorine gas. In this study, it is assumed that the change in the insulating gas does not have any significant influence on the service life and thus the service life can be regarded as the same for all GIS.

Table 1: Determined bandwidth and reference value of the parameters used corresponding to the average switchgear.

For C5-PFK and C4-PFN, the documentation specifications corresponding to SF_6 have been taken into account because of the fluorine gas content.

Category Parameter	Annually	One-time	Special condition
Procurement		2,3 – 23,5 h [6h]	
Labor costs			35 – 100 €/h [67,5 €/h]
Installation		480 – 4.500 € AIS [3.326 €] GIS [3.275 €]	
Replacement/ Dismantling		525 – 6.800 € [3.980 €]	
Documentation requirements (without F-Gas)		0,8 – 18,8 h [4,1 h]	
Documentation requirements (with F-Gas)	0,17 – 4,7 h [1,44 h]	0,8 – 18,8 h [4,7 h]	
Provision of premises			70 – 200 €/m³ [135 €/m³]
Safety management for insulating gases (F-Gas)	0,0 – 5,9 h [0,44 h]		
Safety management for insulating gases (F-gas-free)	0,0 – 1 h [0,25 h]		
Safety management for insulating gases (AIS)	0 h [0 h]		
Downtime losses			0 - 2,200 €/day [0 €/day]
Downtime maintenance GIS	2 h [2 h]		
Downtime maintenance AIS	2 h [2 h]		

Downtime safety test GIS	0,8 h [0,8 h]		
Downtime safety test AIS	0,8 h [0,8 h]		
Maintenance GIS [For reference value, refer to explanation on assumptions].	8 – 540 € [5 €]		
AIS maintenance	65 – 500€ [265 €]		
Inspection	0,25 – 3,3 h [1,1 h]		
Safety test	22 – 500 € [85 €]		
Energy loss GIS	974 – 1.408 kWh [1.186 kWh]		
Energy loss AIS	1.420 – 2.054 kWh [1.730 kWh]		
Energy price (electrical)			3,42 – 17,81 ct/kWh [10,61 ct/kWh]
Transport		100 – 420 € [200 €]	
Disposal		105 – 900 € [280 €]	
Recycling of fluorine gases		260 – 390 € [270 €]	
CO_2-certificates			55 – 350 €/t CO_2 [109,5 €/t CO_2]
Emission factor (power mix)			0,2 – 0,6 kg CO_2/kWh [0,4 kg CO_2/kWh]
Lifetime			GIS: 40 years [40 years] AIS: 40 years [40 years]
Purchase price GIS with SF_6 & AIS (established technology)			8.925 – 12.075 € [10.500 €]
Purchase price GIS with alternative insulating gas mixtures			10.455 – 14.150 € [12.300 €]

Explanations of the assumptions

The purchase price is assumed to be uniform within a range of ±15% for the distribution classes of the established technology. Since the alternative insulating gases or insulating gas mixtures C5-PFK, C4-PFN and CNA are not yet available without restrictions, an additional price per switchgear panel is assumed in this study, taking into account report C2020 6635 [3]. This assumption is for a point in time when the alternative insulating gas mixtures are commercially available and prices have settled.

For the switchgears in secondary distribution, a more significant additional price is seen, according to [3]. An additional price of 20% was used for the calculation of the switchgear in secondary distribution and an additional price of 10% for the switchgear in primary distribution. This is to account for the substitution of SF_6 load-break switches in switchgear in secondary distribution. Manufacturer costs up to this point are not included.

In addition to the required tests according to DGUV, the safety tests also include the tests according to VDE AR-N 4110. These tests must be repeated after 4 years at the latest, which is not handled uniformly according to the expert interviews. For better calculation, they were converted to an annual expense. Taking into account the number of switchgear panels in the switchgear system, this results in a time expenditure of approximately 0.8 hours as an annual equivalent for the entire switchgear. Effort, costs and frequency of the tests vary according to the type of protection used, the location of the switchgear and other general conditions and events. These can lead to significantly shorter intervals, but also to a lower effort than used here.

For the maintenance, in particular the cleaning of the AIS switchgear panels, it is assumed that parts of the annual tasks can also be carried out during the safety inspection.
For the GIS panels, information on maintenance costs varies widely. Manufacturers specify these panels as maintenance-free, which does not mean that certain measures are not appropriate to increase the service life or to eliminate possible sources of interference.
Due to the design, some measures that are necessary for AIS control panels are not possible for GIS control panels, and others are only possible at a significantly higher cost. Nevertheless, according to the answers given in the interviews, operators carry out some maintenance measures that are more costly for GIS control panels than for AIS control panels.
The expert interviews therefore show a very wide spectrum for the maintenance costs. Since the interviews are not representative in scope, the study uses the manufacturers' expected maintenance costs. The spectrum of responses obtained from the interviews and according to manufacturer data is shown in Table 2 below. It must be taken into account that the switchgear under consideration consists of a share of primary switchgear panels and an RMU.

Table 2: Determined bandwidth and reference value of the used parameters according to the average switchgear

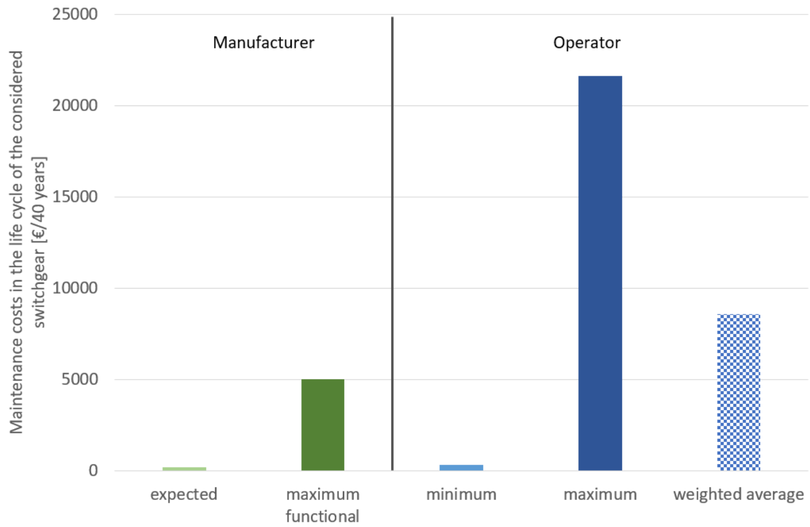
Maintenance costs	Expected (manufacturer)	Maximum practical (manufacturer)	Minimum (expert interviews)	Maximum (expert interviews)	Weighted average (expert interviews)
Cost per year	5 €	125 €	8 €	540 €	215 €
Cost per lifecycle (40 years)	200 €	5.000 €	320 €	21.600 €	8.600 €

The interviews show that maintenance measures are also carried out that manufacturers do not expect for GIS and do not regard as expedient. The study cannot clarify whether the maintenance measures carried out are necessary.
Based on the spectrum, it can be seen that maintenance is more important for some operators, while it is less important for others.
In the case of switchgear in primary distribution, the interviews show that industrial network operators spend more effort on maintenance than public network operators. In the case of RMUs, the spectrum is also very wide among public network operators.

In general, the expert interviews show that operators carry out more maintenance than is expected from manufacturers, especially for RMUs. On average, industrial network operators calculate more for maintenance than operators of public networks.

Figure 4 shows the maintenance costs over a life cycle of 40 years according to the various data. The weighted average value from the expert interviews is significantly higher than what manufacturers consider appropriate. As with the other parameters, the answers to the weighted mean value have been multiplied by the number of corresponding switchgear systems or switchgear panels

Figure 4: Comparison of maintenance costs from the perspective of the manufacturers and the expert interviews



In addition to the scope of maintenance measures and the conditions for the cost of maintenance, the intervals at which maintenance is carried out are decisive. If maintenance is carried out every 2 years, the costs related to the life cycle are of course significantly higher than for a maintenance interval of 5 years, despite the same individual expenditure.

2.1 Cost categories

The total costs incurred are broken down into the following cost areas:

- Acquisition
- Operation
- Plant inspections
- CO_2 costs
- End of life

Figure 5 to Figure 9 show the calculation of the individual cost areas and the parameters entered there. The coloring of the cost areas acquisition (black), operation (dark blue), plant inspections (gray), CO_2 costs (red) and end of life (green) also corresponds to the coloring in Figure 11 for the share of the individual cost categories in the total costs.

Cost category acquisition:

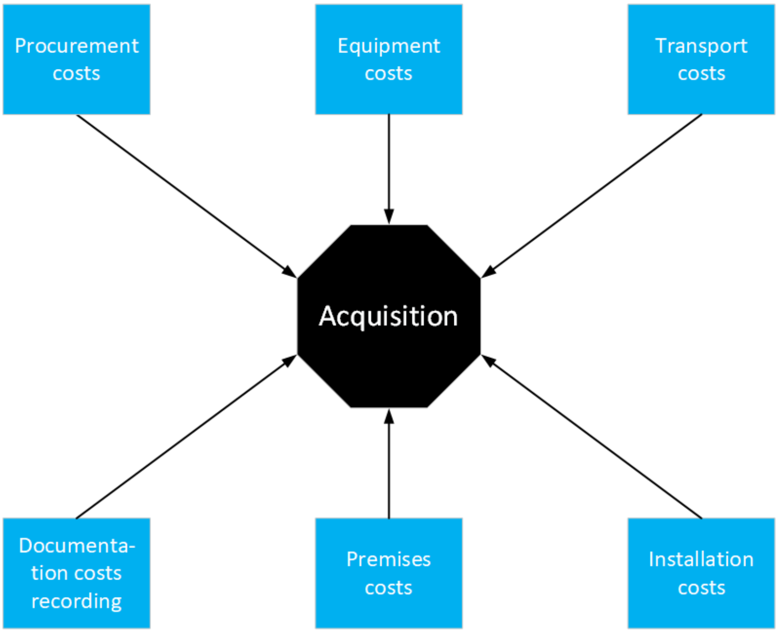
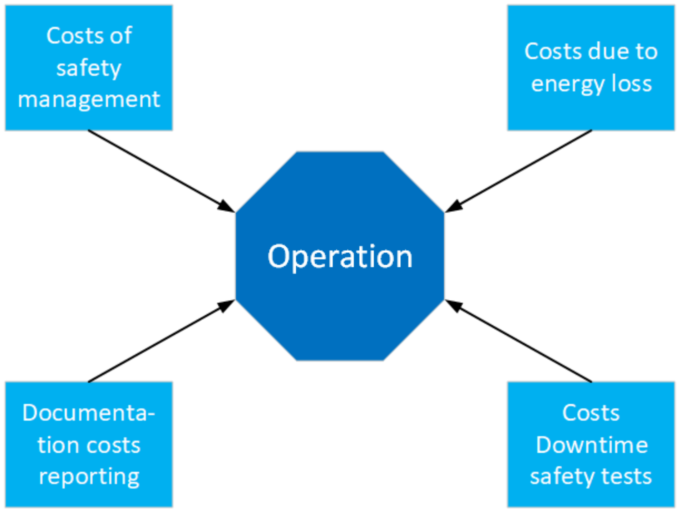


Figure 5: Cost factors affecting the category of acquisition

The acquisition cost category (black), Figure 5, is composed of the purchase price, the cost of transportation, the cost of installation, the cost of the premises, and the product of the safety management effort and the labor cost. In addition, from the product of the effort of documentation for the registration of the switchgear and the labor costs.

Figure 6: Cost factors that affect the category of operation

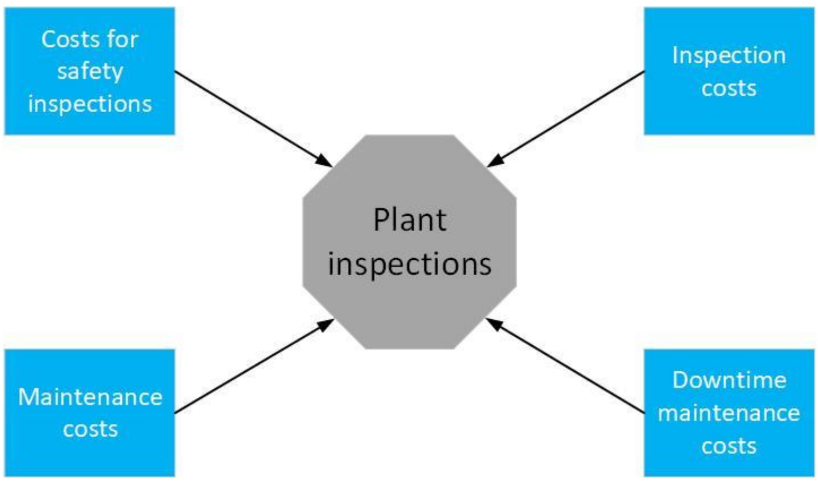
Cost category operation:



The cost category operation (dark blue), Figure 6, is composed of the cost factors costs due to loss energy, costs of safety management, documentation costs reporting and costs downtime safety tests

Cost category plant inspections:

Figure 7: Cost factors that affect the category of plant inspections



The cost category plant inspection (gray), Figure 7, consists of the cost factors: Inspection costs, Costs for safety tests, Maintenance costs and the Downtime maintenance costs.

Category CO_2 costs :

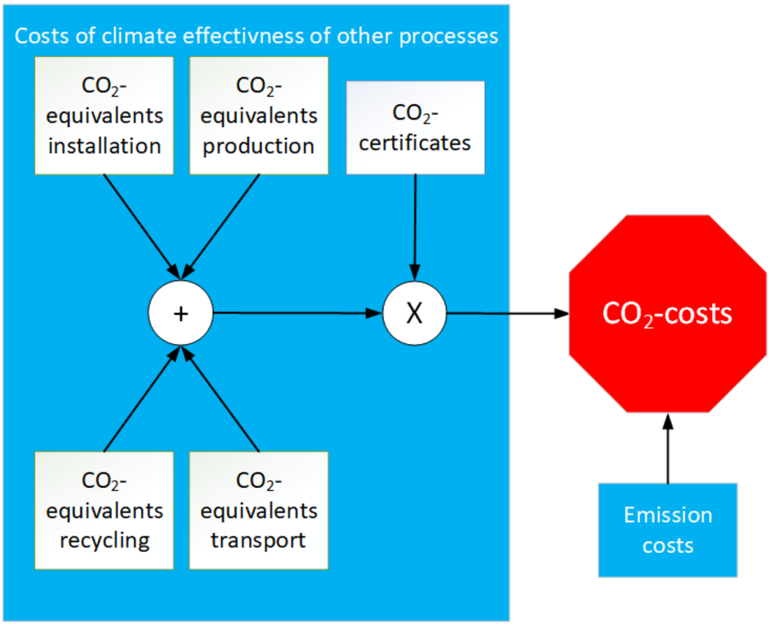


Figure 8: Cost factors affecting the category of CO_2 costs.

The cost category CO_2-costs (red), Figure 8, consists of the emission costs and costs of climate effectiveness of other processes. The costs of climate effectiveness of other processes include the CO_2 equivalents of the processes production, installation, transport and the recycling of materials after disposal and are multiplied by the costs for the CO_2 certificates. In this study, the climate impact and thus the CO_2 equivalents of these processes are assumed to be the same for all products.

Cost category End-of-life:

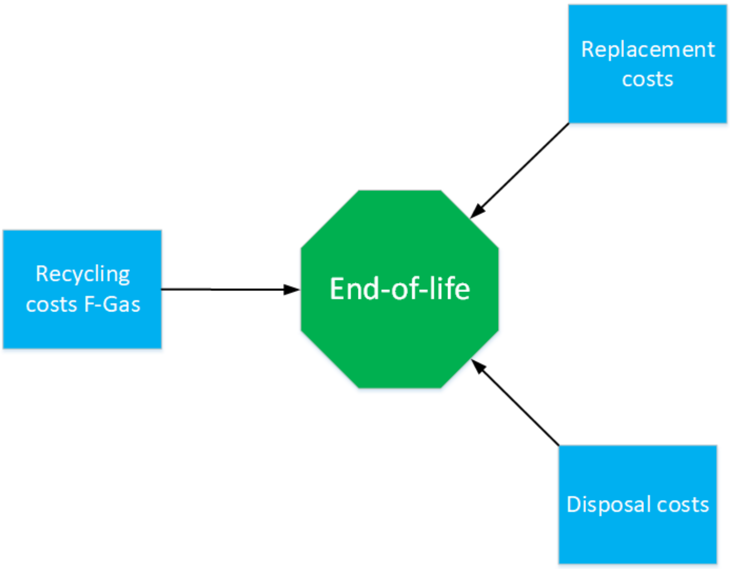


Figure 9: Cost factors impacting the category End-of-life.

The category end-of-life cost (green), Figure 9, is composed of the determined costs for replacement (dismantling), the disposal costs and the recycling costs F-gas.

3 Sensitivity analysis

The sensitivity analysis provides the statement which cost factors have a high influence on the total costs during the observation period. For this purpose, the individual factors are changed and their influence on the total costs is considered. From the influence, it can be derived which factors are a lever with which the total costs can be significantly changed.

3.1 Total costs of the facilities.

Figure 10 shows the total costs in the observation period of 40 years (10a) and 60 years (10b) for the different switchgear types. The values are related to the GIS SF_6 switchgear type, since this type is established and switchgears with SF_6 will be replaced by other types in the future.

The F-gas containing switchgear is 3.4% more expensive for an observation period of 40 years, and 4.4% more expensive for an observation period of 60 years, rounded in the figures. The GIS CNA, on the other hand, is 8.7% and 6.5% less expensive than the GIS SF_6 switchgear.
This shows that the advantage in the purchase price of SF_6 over CNA is more than used up during the life cycle, due to other cost factors.
For the air-insulated switchgear (AIS), the total costs add up to 132.0% for an observation period of 40 years, or 127.2% for 60 years. If the residual value of the respective switchgear is taken into account, the relative difference between the observation periods is smaller.

If the minimum parameter values are used and the switchgear type GIS SF_6 is kept as a basis, the evaluation changes. Then the GIS CNA type is 5.5% more expensive than SF_6, while GIS C5-PFK and GIS C4-PFN are 9.0% more expensive. The AIS system is then 9.9% more expensive than the GIS SF_6.

Some of the cost factors are strongly dependent on the number of panels or the division of secondary and primary panels, especially the "cost of safety checks" and consequently the "cost of downtime safety checks", which are the same for all types of switchgears. However, these are avoided as far as possible, e.g. by optimized combination of different measures, and are therefore not shown here.
In addition, the energy loss is also dependent on the number of fields, as are the disposal costs, the recycling costs, the installation costs, the replacement costs, the transport costs and the equipment costs.
The documentation costs and inspection costs depend on the number of switchgear systems or gas containers.

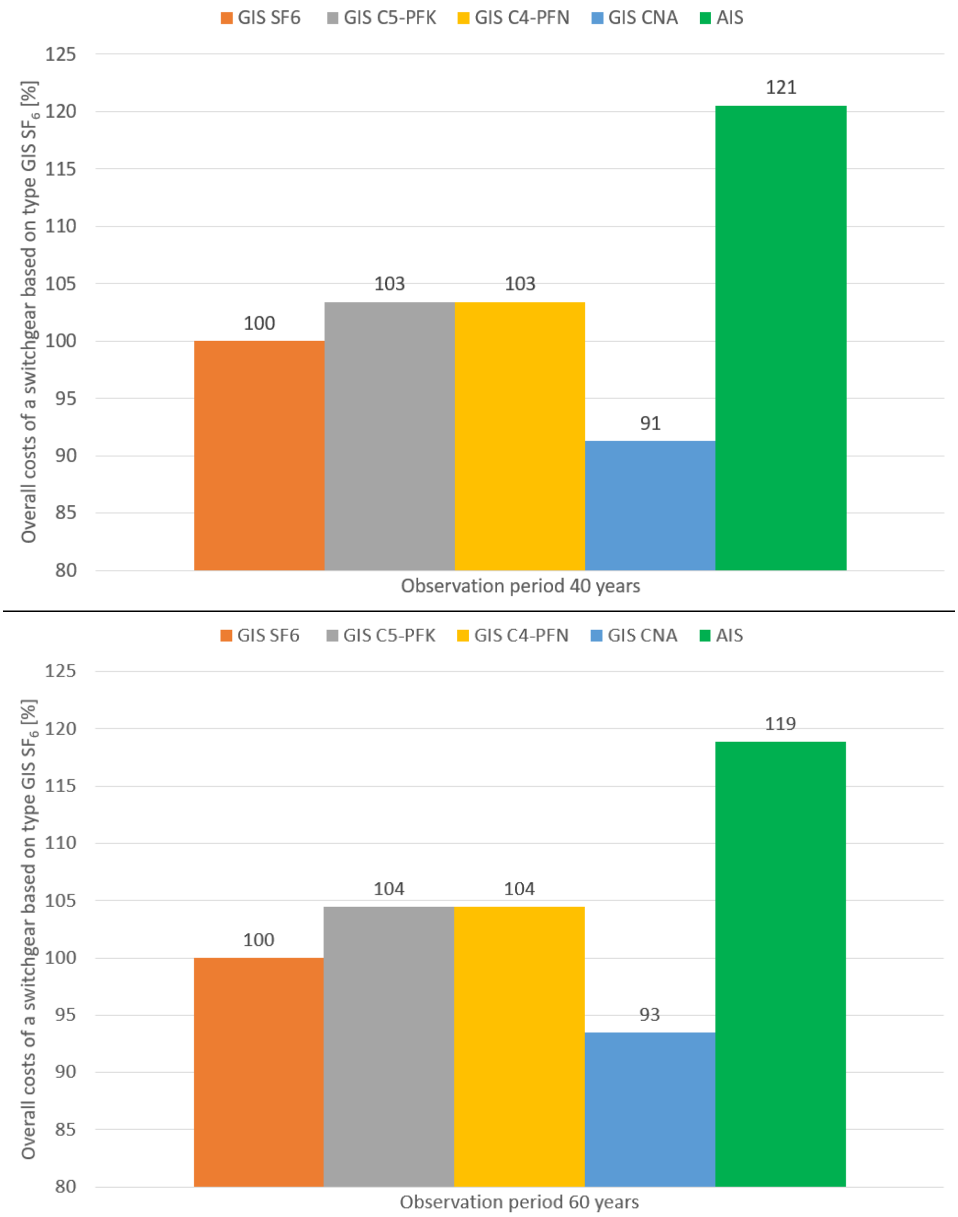


Figure 10: Overall costs by switchgear type

(10a) Observation period of 40 years (top)

(10b) observation period of 60 years (bottom)

GIS - gas-insulated switchgear
AIS - air-insulated switchgear
SF_6 - sulfur hexafluoride
C5-PFK - perfluoroketone
C4-PFN - perfluoronitrile
CNA - Components of Natural Air

For C5-PFK and C4-PFN, the documentation requirements corresponding to SF_6 have been taken into account due to the fluorine gas content.

3.2 Composition of costs

Figure 11 shows how the overall costs of the respective switchgear type are made up of the cost areas.
Acquisition, plant inspection and operation account for the largest share.
The CO_2 costs account for approx. 5.5% to 7.0% of the respective total costs.
Acquisition contributes approximately 32.1% to 47.1% for each of the switchgears.
Operation accounts for between 15.7% and 26.1% of the overall cost in each case, and plant inspection contributes between 16.4% and 36.2%.
End-of-life expenses range from 9.1% to 12.0%.

Accordingly, over 60% of the respective total costs of the switchgear types result from acquisition, with the purchase price of the switchgear, and plant inspection, which also includes the maintenance performed.

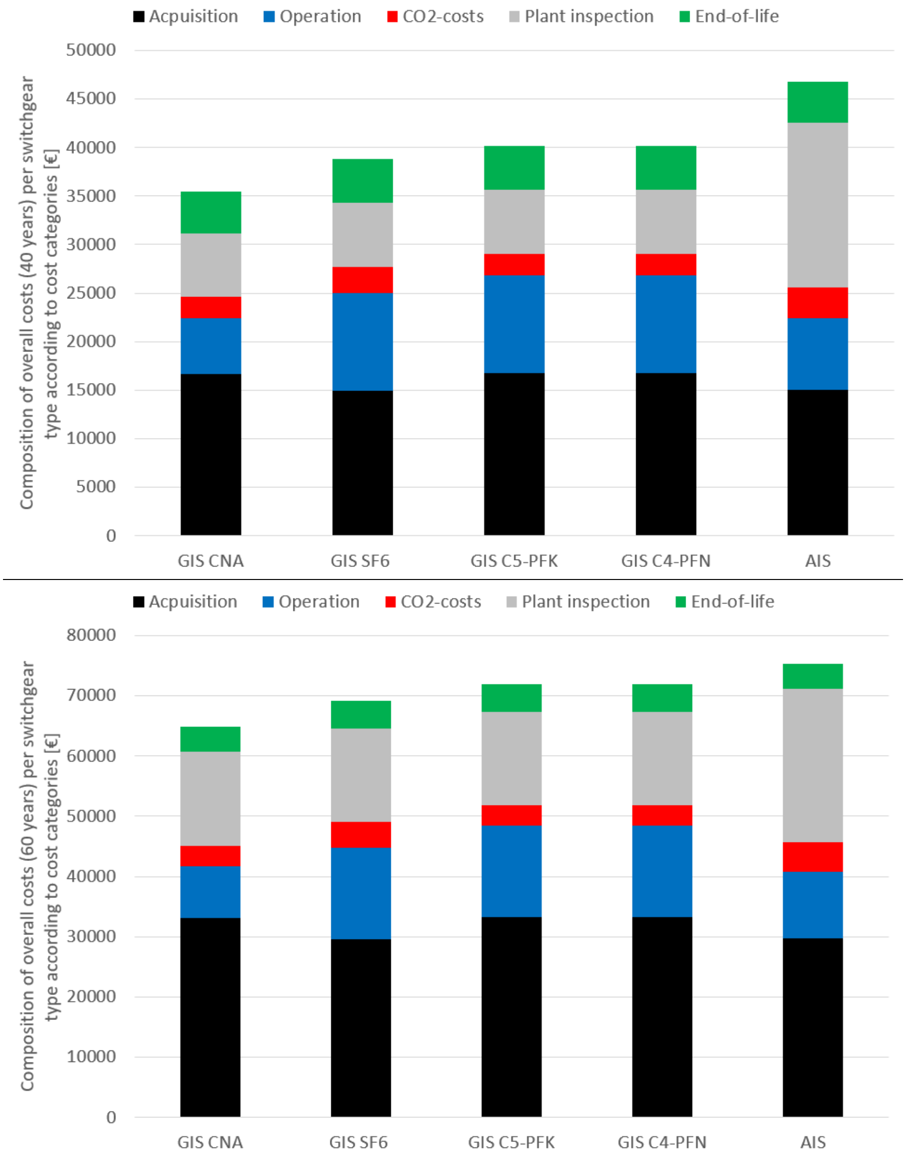


Figure 11: Share of the cost categories in the respective overall costs.

(11a) Representation as a share of the respective overall costs for an observation period of 40 years.

(11b) Comparison of the cost shares of the different switchgear types, for an observation period of 60 years.
GIS - gas-insulated switchgear
AIS - air-insulated switchgear
SF_6 - sulfur hexafluoride
CNA - Components of Natural Air
C5-PFK - perfluoroketone
C4-PFN - perfluoronitrile

For C5-PFK and C4-PFN, the documentation requirements according to SF_6 are taken into account due to the fluorine gas content.

The difference in operating costs, which are higher for the F-gas-containing switchgear than for the F-gas-free switchgear, is striking. These result from the higher requirements in handling the F-gas containing insulating gases and the documentation. While the costs for plant inspections are the same for all GIS, they are significantly higher for AIS.
The price difference between the established switchgear types GIS SF_6 and AIS and the alternative insulating gases GIS CNA, C5-PFK and C4-PFN can be seen in the purchase price.

The differences between the gas-insulated switchgear types are relatively small in terms of CO_2 costs. Due to the high climate effectiveness of SF_6, these are highest for the switchgear with SF_6 among the GIS. In the case of the AIS, the higher loss energy is significant; this caused the highest CO_2 costs in this study due to the current electricity mix.

The difference at End-of-life is small; no significant costs are added by the additional recycling of the F-gas-containing insulating gas, as shown in Figure 12.

3.2.1 Significance of the individual cost factors

The share of the cost factors in the overall costs was determined for the reference values and the minimum and maximum parameter values.

The reference values were used as a basis for sorting the cost factors according to their share of the total costs over an observation period of 40 years.

The cost factors in the following figures are presented according to the order of their share in the overall costs for a CNA switchgear. The cost factors are arranged so that the cost factor with the largest cost is shown at the bottom.
The bars indicate that the order of the cost factors may vary depending on the type of switchgear.

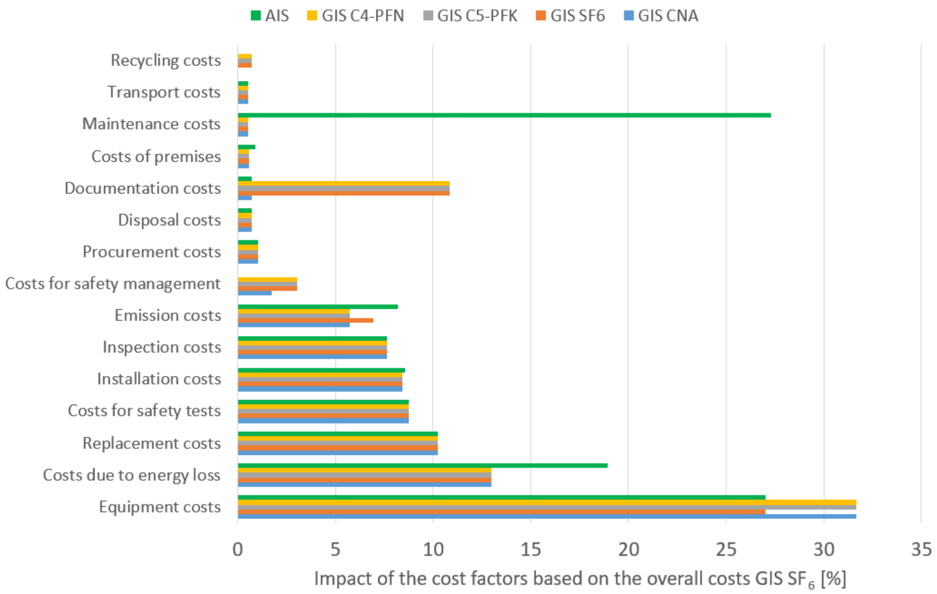


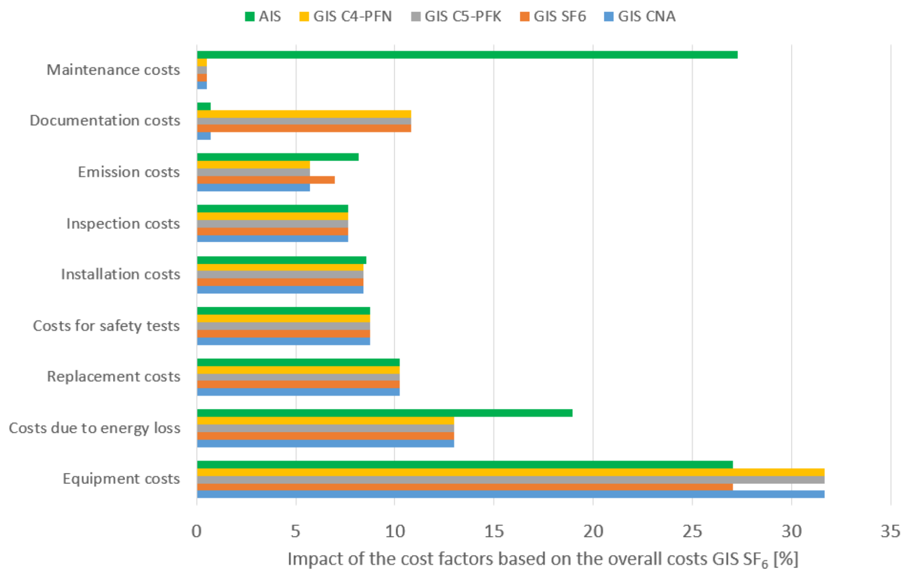
Figure 12: Influence of cost factors on overall costs normalized to GIS SF_6 (observation period of 40 years).
GIS - gas-insulated switchgear
AIS - air-insulated switchgear
SF_6 - sulfur hexafluoride
CNA - Components of Natural Air
C5-PFK - perfluoroketone
C4-PFN - perfluoronitrile

For C5-PFK and C4-PFN, the documentation requirements corresponding to SF_6 have been taken into account due to the fluorine gas content.

In Figure 12 and Figure 13, the cost factors are shown normalized as shares of the total costs (based on the total costs GIS SF_6 = 100%).
In the case of the AIS switchgear, the higher energy loss can be seen well, both in the costs due to lost energy and in the emission costs.
Figure 13 shows a selection of the cost factors, with at least 5% of the overall costs.

Figure 13: Influence of cost factors on overall costs normalized to GIS SF_6 (observation period of 40 years) - selection the largest factors.
GIS - gas-insulated switchgear
AIS - air-insulated switchgear
SF_6 - sulfur hexafluoride
CNA - Components of Natural Air
C5-PFK - perfluoroketone
C4-PFN - perfluoronitrile

For C5-PFK and C4-PFN, the documentation requirements according to SF_6 are taken into account due to the fluorine gas content.



The differences in cost factors between the GIS switchgear types are shown in more detail in Figure 14.

The recycling costs are the same for the types that use F-gases. Possible decomposition products are not taken into account.
Due to the short availability of such switchgears on the market so far, there are no empirical values for the recycling of C4-PFN and C5-PFK. Therefore, costs corresponding to the recycling of SF_6 are assumed here. Type CNA does not contain F-gases, which are specifically recycled.

The documentation costs show the costs for the annual documentation and reporting of the F-gas quantities in the inventory. Since the same documentation requirements are assumed for the switchgear types with F-gases, the costs are also the same, while these costs are significantly lower (approx. 10% of the total costs) for switchgear types without corresponding gas components.

For the emission costs, differences arise for the GIS due to climate-relevant emissions (considered as CO_2 equivalents) of fluorine-containing gases or gas mixtures that switchgears exhibit over their lifetime and during the recycling process. Leakage rates during these life stages are assumed to be the same, but the climate impact of the insulating gases is different.
Switchgear manufacturers of fluorine-containing and fluorine-free insulating gases report leakage rates as 0.1% p.a., according to IEC 62271-1:2017 [17], Section 6.16.4. Emissions during disposal and recycling are assumed to be the same in a range (1.5 - 10% [2%]) according to [1, 2] for the switchgear types.
As a consequence, the costs for the CNA type are low, since a gas mixture with low (<1) climate impact is used there.
For switchgears using C5-PFK with a climate effectiveness of <1 (CO_2 equivalent) [18], the costs are comparable.
Switchgears using C4-PFN also hardly incur higher costs despite a climate effectiveness of 292 [19], since only small masses of this substance are used.
The climate effectiveness of these 3 gas mixtures depends on the mixture ratio used. In the case of CNA and C5-PFK, the CO_2 component with a value of 1 has the greatest climate effectiveness of the components, and in the case of C4-PFN, the pure

Novec 4710 compound with a value of 2,100. In the case of switchgears with SF_6 and its climate effectiveness of 22.800 [20], higher costs arise in this area.

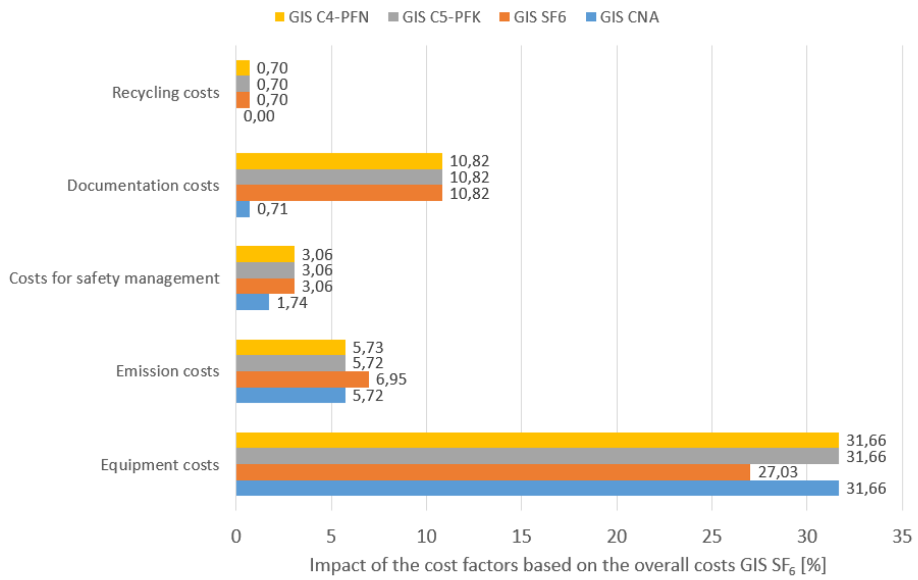


Figure 14: Influence of cost factors, with differences for GIS switchgears (observation period of 40 years).

GIS - gas-insulated switchgear
SF_6 - sulfur hexafluoride
CNA - Components of Natural Air
C5-PFK - perfluoroketone
C4-PFN - perfluoronitrile

For C5-PFK and C4-PFN, the documentation requirements corresponding to SF_6 have been taken into account due to the fluorine gas content.

For the F-gas containing switchgear types, higher costs are incurred in the safety management for insulating gases, since training contents are carried out for escaping gases or for the handling of such gases.
In addition to the climate impact, there are further environmentally relevant properties [10, 11] of the gases and their possible decomposition products in the case of C5-PFK and C4-PFN, which justify the assumption of higher costs compared to CNA. Whether the effort will be comparable to SF_6 or greater due to these properties cannot be evaluated here, since there are currently neither empirical values nor specifications on this. The difference in the costs for safety management between GIS with F-gas containing insulating gas and insulating gas without F-gas is more than 1.4% of the total costs.

For the cost factor equipment costs, different prices were determined based on manufacturer data (see chapter 2.2). GIS with SF_6 as insulating gas, as an established technology, causes lower costs in this point.

The following figures show the evaluation for the observation periods 40 years, 50 years and 60 years as well as the presentation of the range for the cost factors.

Effects of the observation period

From the change in the observation period, Figure 15 to Figure 19, it can be seen which cost factors are directly linked to individual events or the service life and which have an effect on the total costs over time. The reference values used can be found in Table 1. The equipment costs do not take into account any residual value of the switchgear at the end of the observation period: Switchgear panels of standard switchgear systems in particular can still be used in other switchgears after 10 (observation period 50 years) or 20 (observation period 60 years) years of operation. Since the determination of the residual value is not uniform among the various operators, the following graphs show the investment costs incurred.

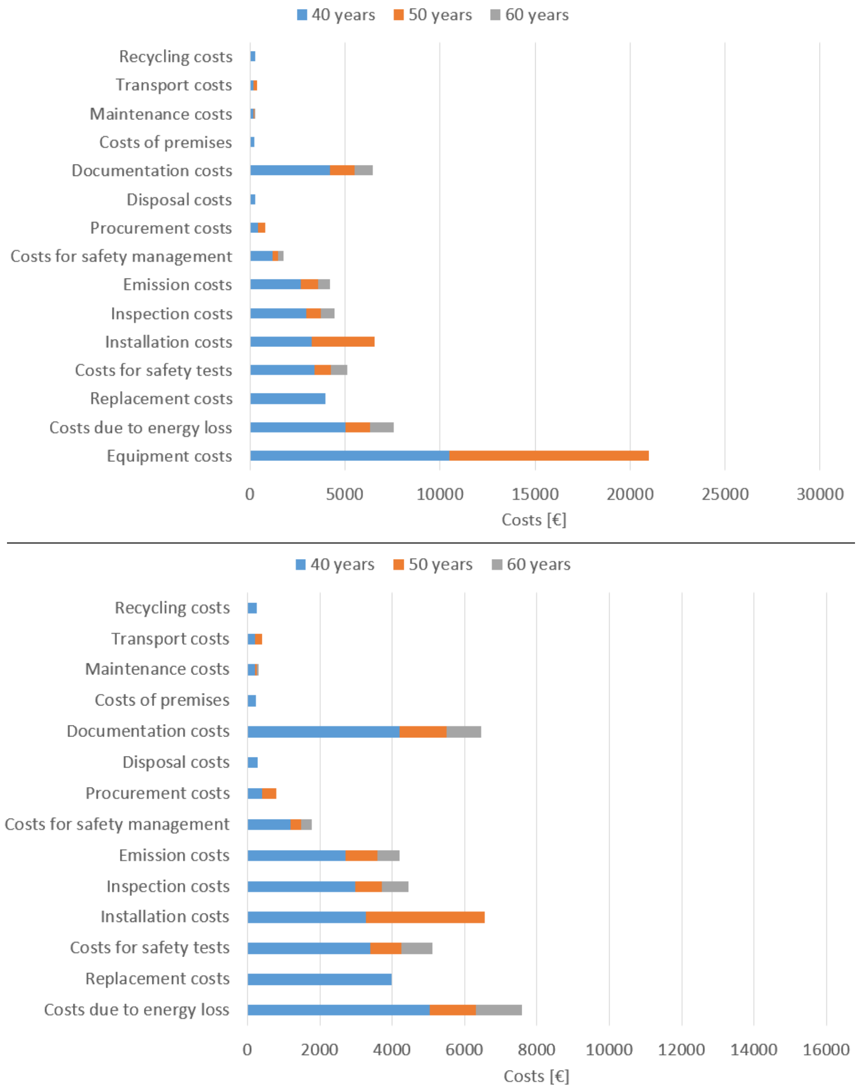
Figure 15: Cost factors for different service lives. GIS SF_6 (reference values according to Table 2)

(15a) All cost factors

(15b) Zoom in cost factors with smaller contributions.

GIS - Gas Insulated Switchgear

SF_6 - sulfur hexafluoride



Especially equipment costs and installation costs stand out in this representation, since with these, larger amounts arise at a defined time. Whereas other cost factors, such as transport costs or procurement costs, are smaller or, like inspection costs, are incurred continuously.

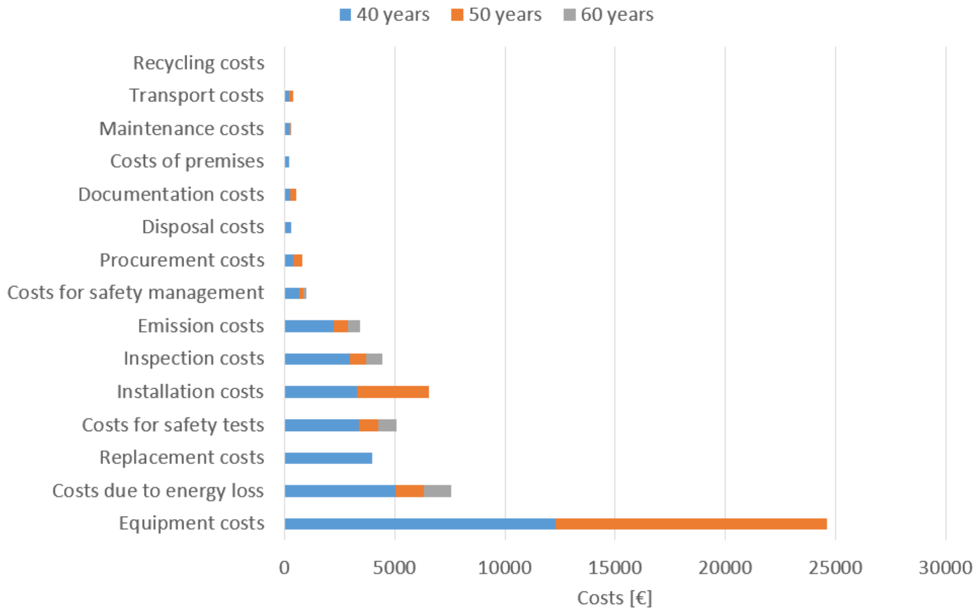
Figure 16: Development of cost factors over the service life. GIS CNA (reference values)

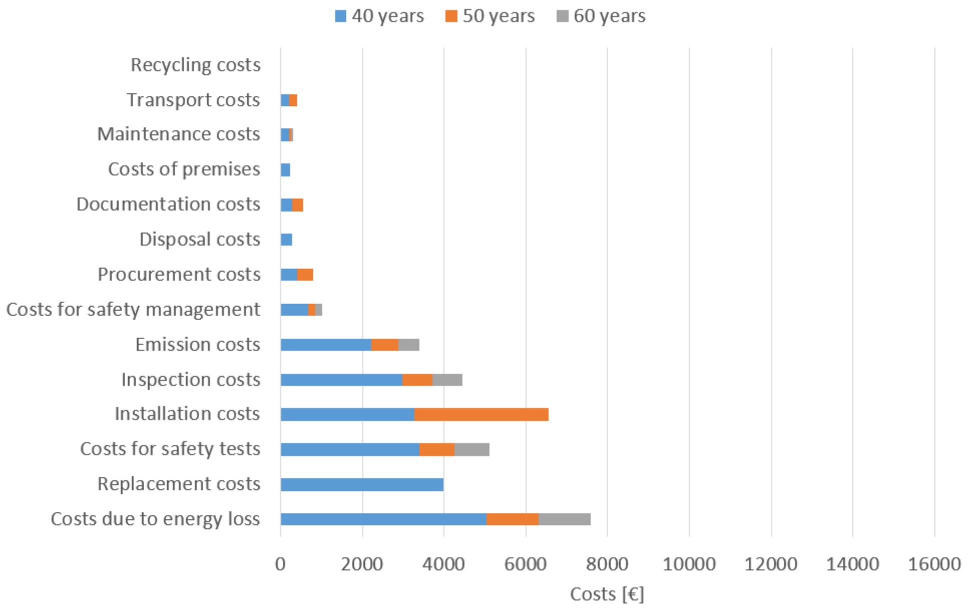
(16a) All cost factors

(16b) Zoom in cost factors with smaller contributions.

GIS - gas insulated switchgear

CNA - Components of Natural Air





Sensitivity analysis

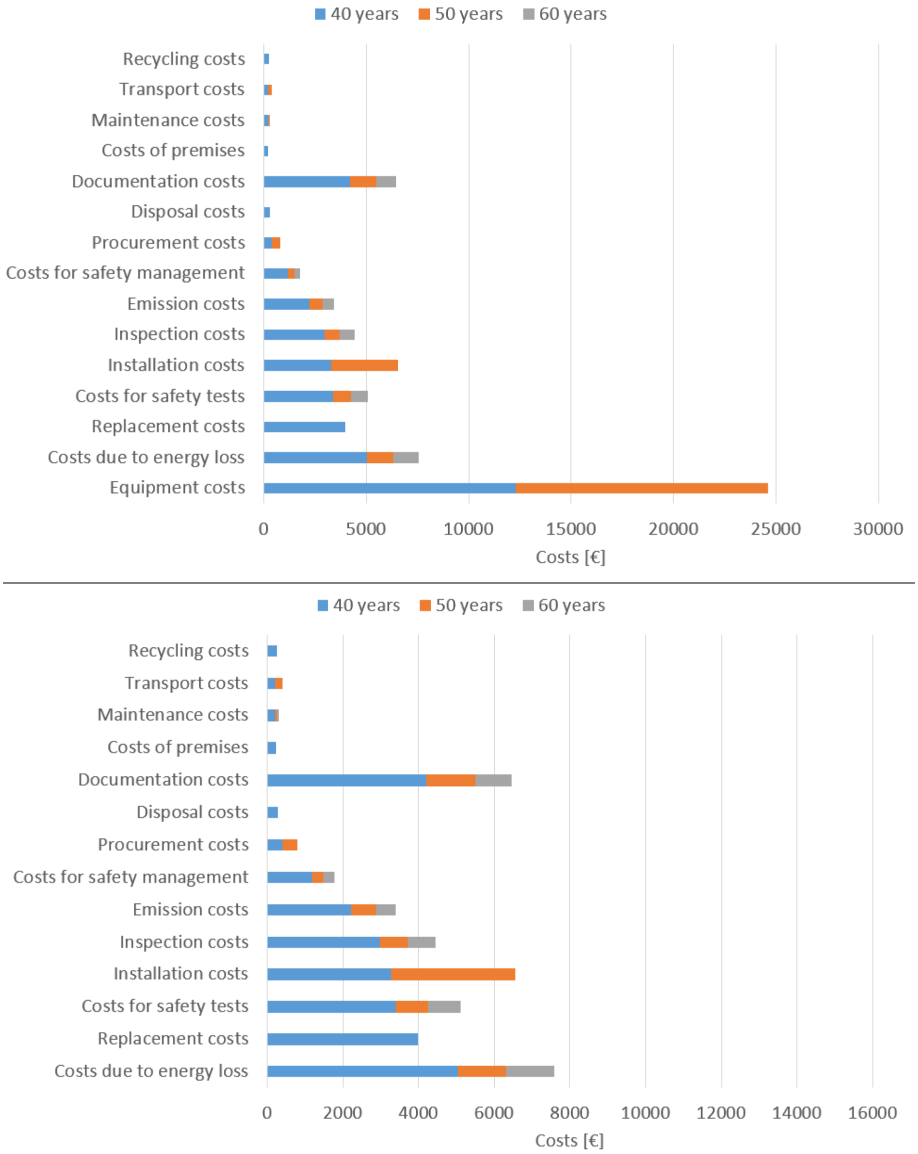
Figure 17: Development of cost factors over the service life. GIS C5-PFK (reference values)

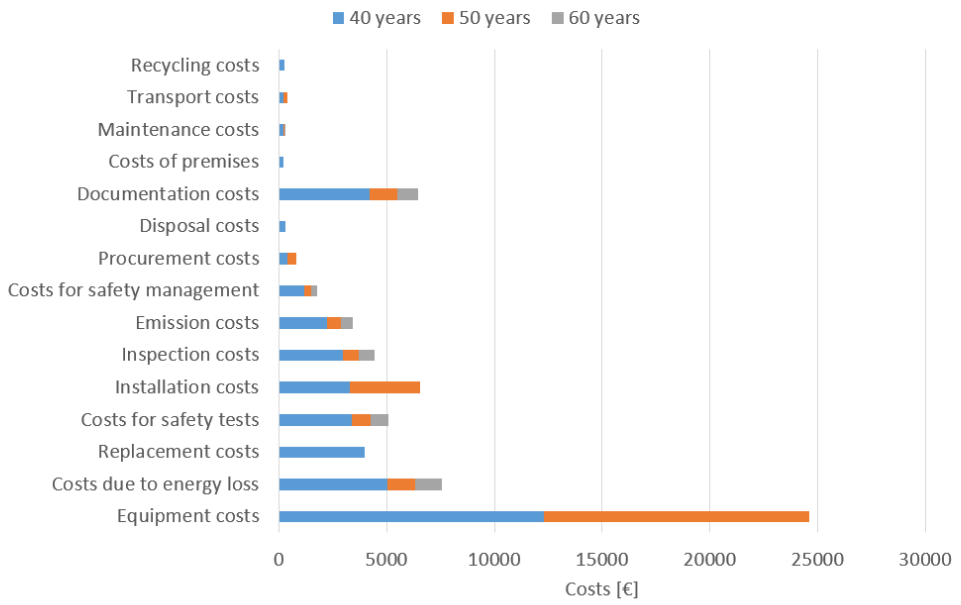
(17a) All cost factors

(17b) Zoom in cost factors with smaller contributions.

GIS - gas-insulated switchgear
C5-PFK - perfluoroketone

For C5-PFK and C4-PFN, the documentation requirements corresponding to SF_6 are taken into account due to the fluorine gas content.





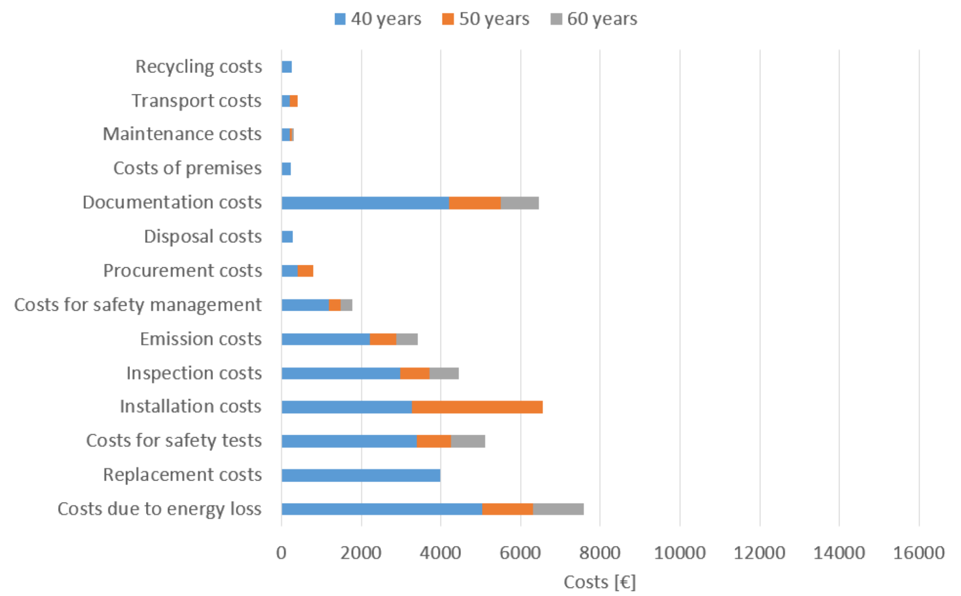


Figure 18: Development of cost factors over the service life. GIS C4-PFN (reference values)

(18a) All cost factors

(18b) Zoom in cost factors with smaller contributions.

GIS - gas-insulated switchgear
C4-PFN - perfluoronitrile

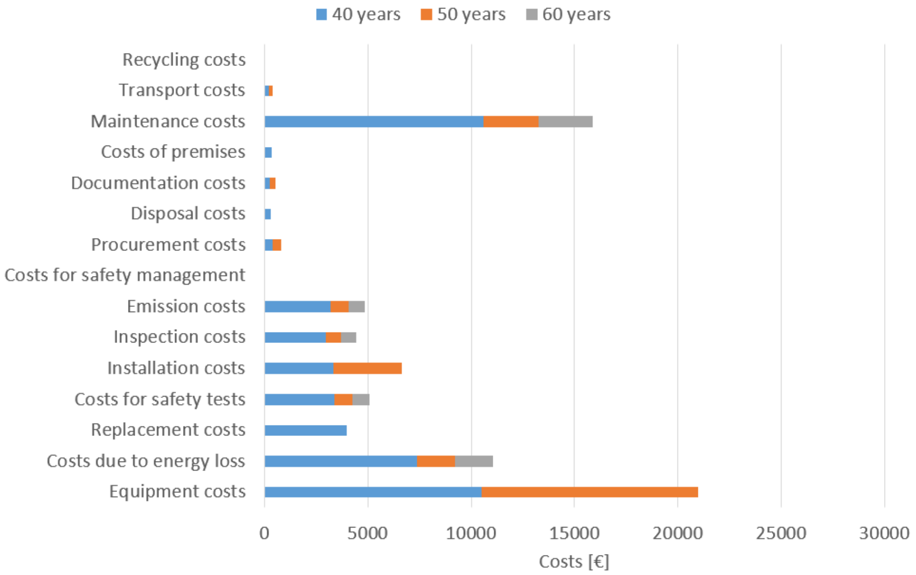
For C5-PFK and C4-PFN, due to the fluorine gas content, the documentation specifications corresponding to SF_6 have been taken into account.

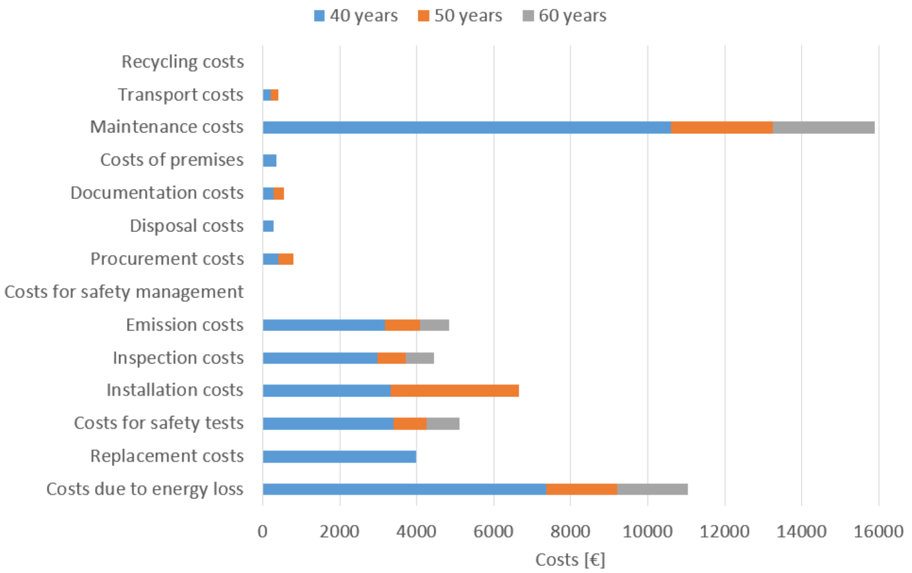
Figure 19: Development of cost factors over the service life. AIS (reference values)

(19a) All cost factors

(19b) Zoom in cost factors with smaller contributions.

AIS - air-insulated switchgear





Since the literature indicates a shorter service life for AIS than for GIS, a shorter service life is shown here as an example for an AIS system with an observation period of 40 years to 60 years. Figure 20 shows the cost categories for different observation periods for an AIS with a 30-year service life. The shorter lifetime for the exemplary switchgear changes the picture of the costs, since some costs are incurred earlier. With an observation period of 40 years, a 2nd switchgear must therefore already be procured. The residual value of the system is not considered in the equipment costs.
If the results for the life cycles are compared, there is a shift in time for some costs that are incurred at the time of acquisition (such as the equipment costs) or at the end of life. Because these costs are incurred at defined points in time, they are very sensitive with regard to the selected observation period.

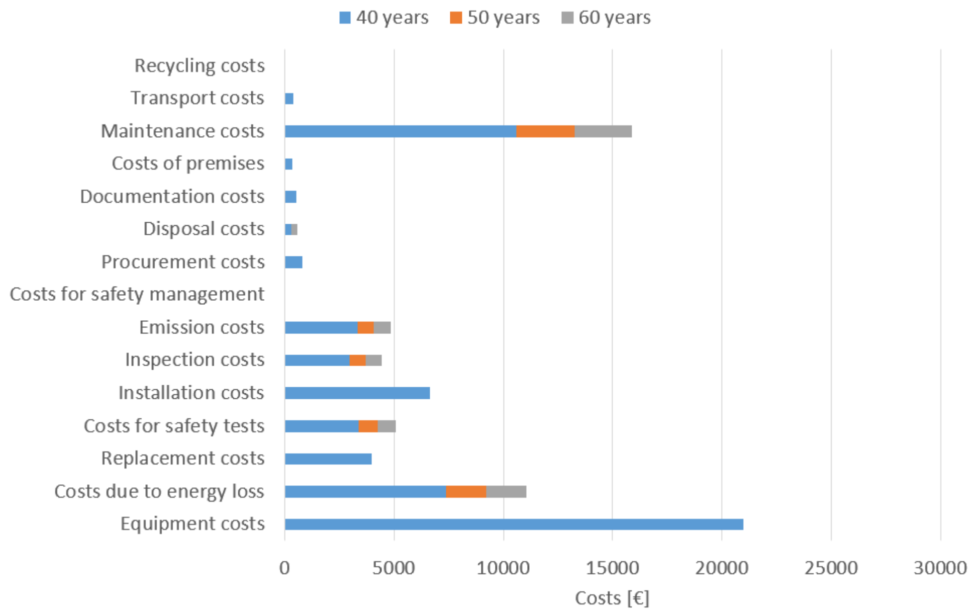


Figure 20: Development of cost factors over the service life. Changes for AIS with 30-year service life (reference values).

AIS - air-insulated switchgear

For individual cost factors, it is decisive which observation period, in relation to the service life, is selected. One-off costs, such as the "cost of premises", are only paid once, for example, when the switchgear is newly acquired or purchased. Annual costs, on the other hand, add up continuously and thus gain relative importance. Accordingly, cost factors that are incurred in particular at the time of acquisition and at the end of life are sensitive to the exact times for the start and end of the observation, while the more continuously incurred costs are sensitive to the total length of the observation period. This can be seen in the cost factors "costs for replacement" and "costs for safety inspections". For the 40-year observation period, the "cost of replacement" is higher, while for the 60-year observation period, the continuous "costs of safety tests" is higher, since no replacement takes place in the additional 20 years, but further safety tests do.

Range of parameters

The effects of the determined range of parameters are shown in Figure 21 to Figure 25 per switchgear type.

The costs due to energy loss and the emission cost have a very wide bandwidth, due to the cost of energy and variation of losses, as well as the emission factor and the price of CO_2 allowances. For the price of CO_2 certificates, the current unclear development gives a wide range. In the appendix Figure 32, some currently discussed scenarios for a development after 2025 are shown as examples.
The costs for safety tests have a very wide range, especially due to the protection tests. Since there are very many different protective functions, the complexity and thus the costs can vary greatly, in addition to the requirements imposed by occupational safety and accident prevention regulations (DGUV). The cost factor is independent of the system type and the insulating gas used.

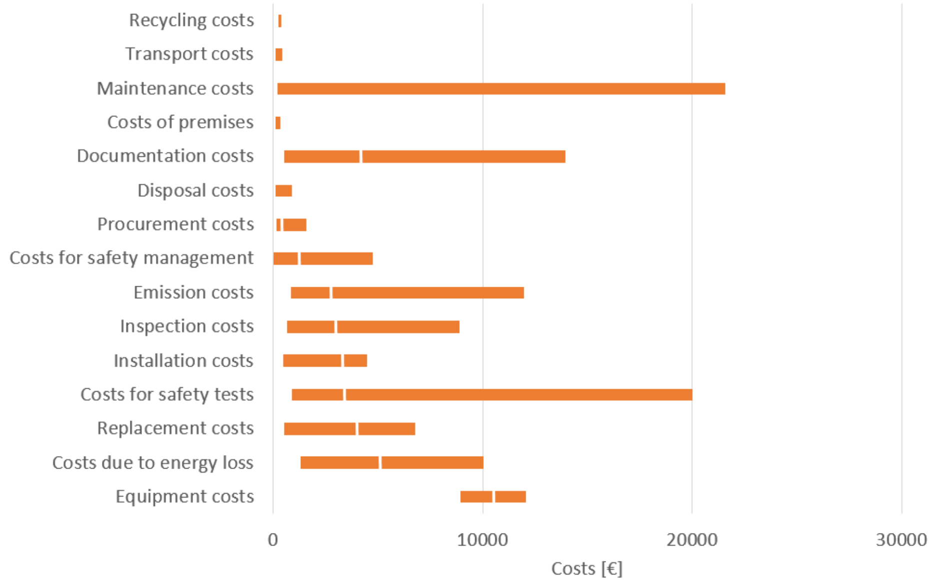
For other cost factors, different handling or prerequisites can be assumed, such as different maintenance intervals and scope, inspection intervals or different requirements for installation and replacement.

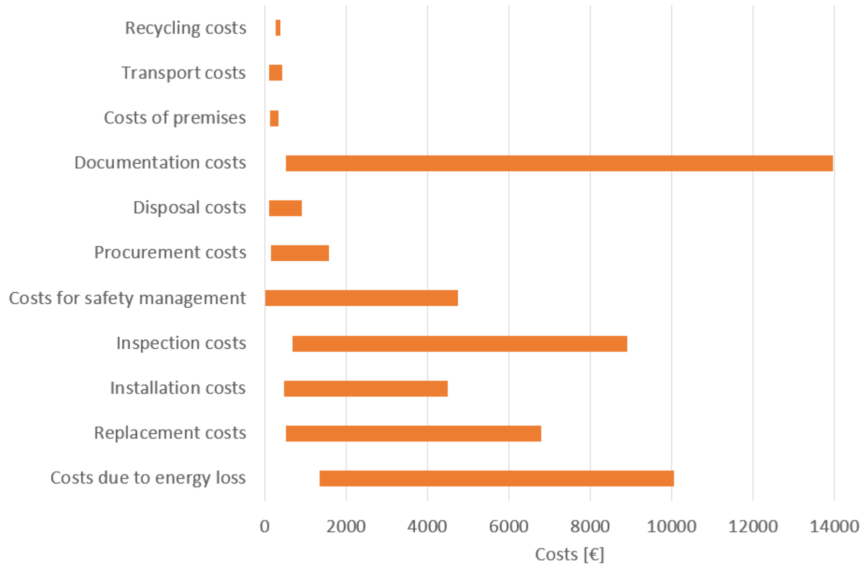
Figure 21: Range of cost factors for an observation period of 40 years. GIS SF_6

(21a) All cost factors

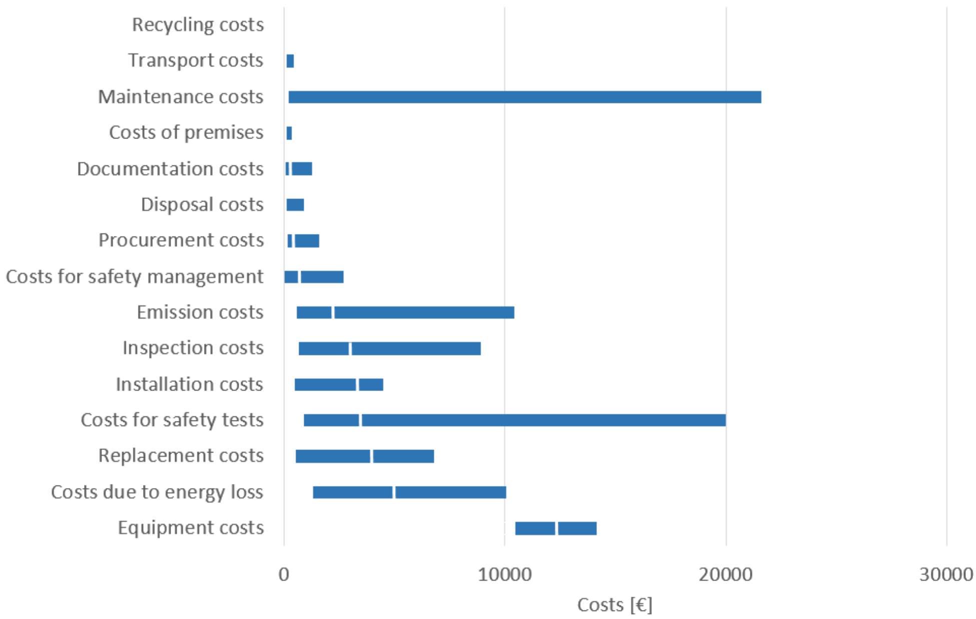
(21b) Zoom in cost factors with smaller contributions. GIS - gas-insulated switchgear

SF_6 - sulfur hexafluoride





In the presentation of all cost factors (as 21a), the reference value is represented by a break in the bar wherever possible.



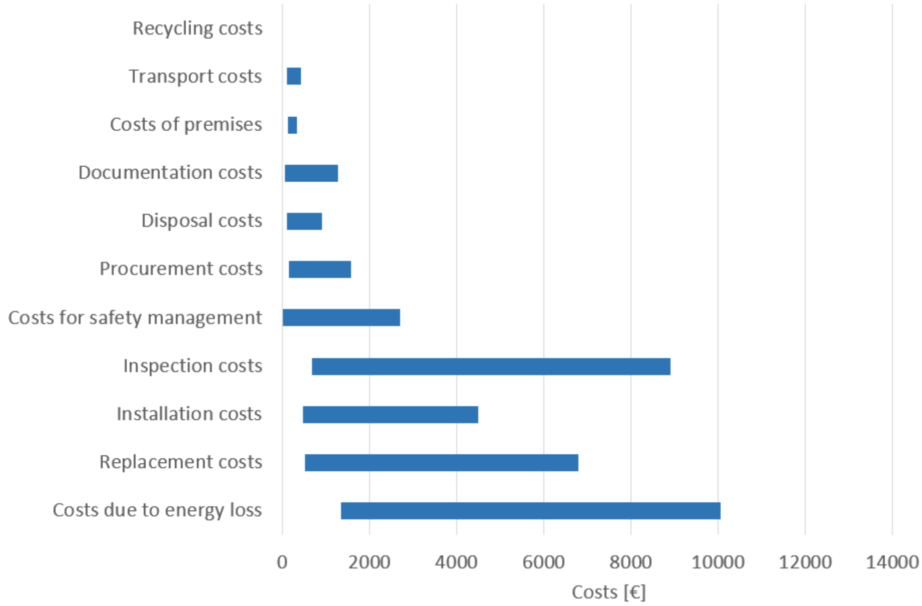


Figure 22: Range of cost factors over a 40-year observation period. GIS CNA

(22a) All cost factors

(22b) Zoom in cost factors with smaller contributions.

GIS - gas-insulated switchgear

CNA - Components of Natural Air

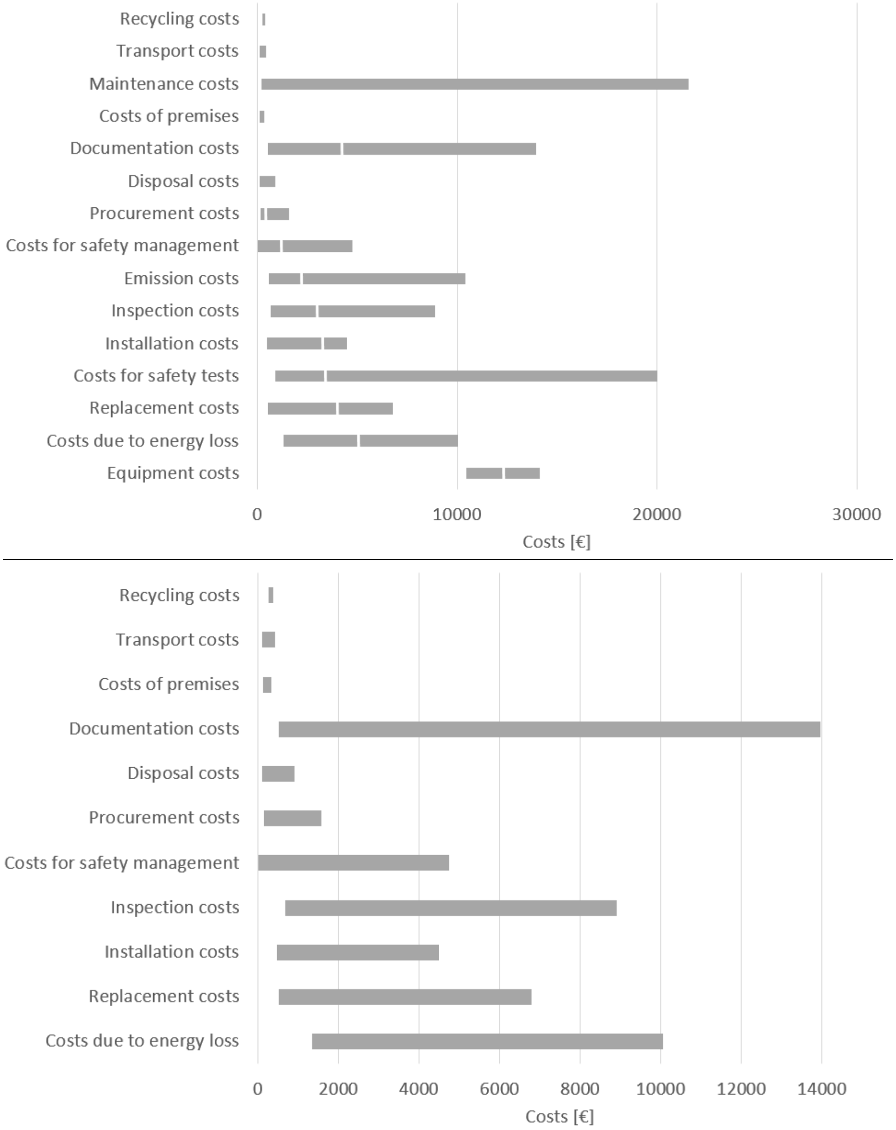
Figure 23: Range of cost factors for an observation period of 40 years. GIS C5-PFK

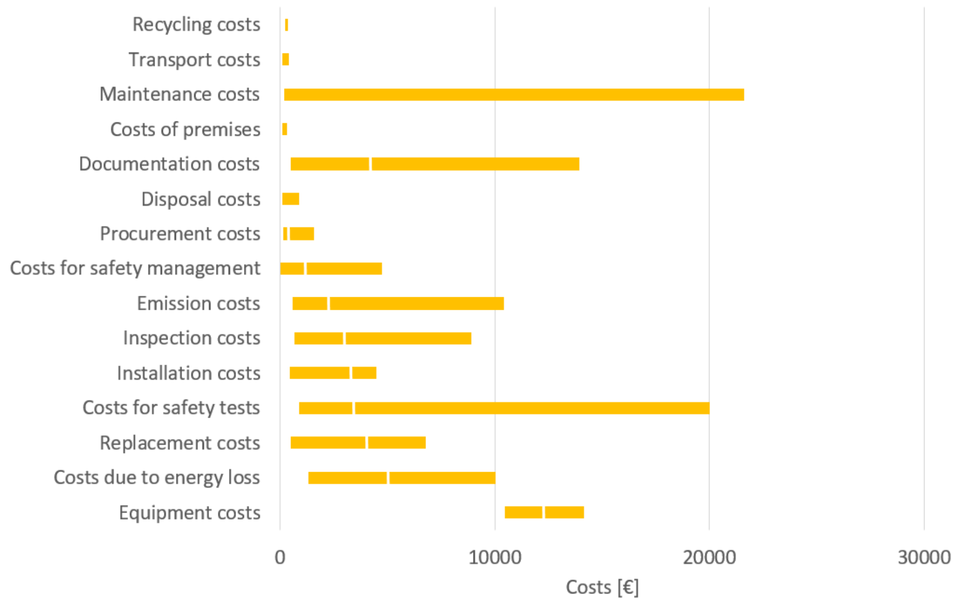
(23a) All cost factors

(23b) Zoom in cost factors with smaller contributions.

GIS - gas-insulated switchgear
C5-PFK - perfluoroketone

For C5-PFK and C4-PFN, the documentation requirements corresponding to SF6 are taken into account due to the fluorine gas content.





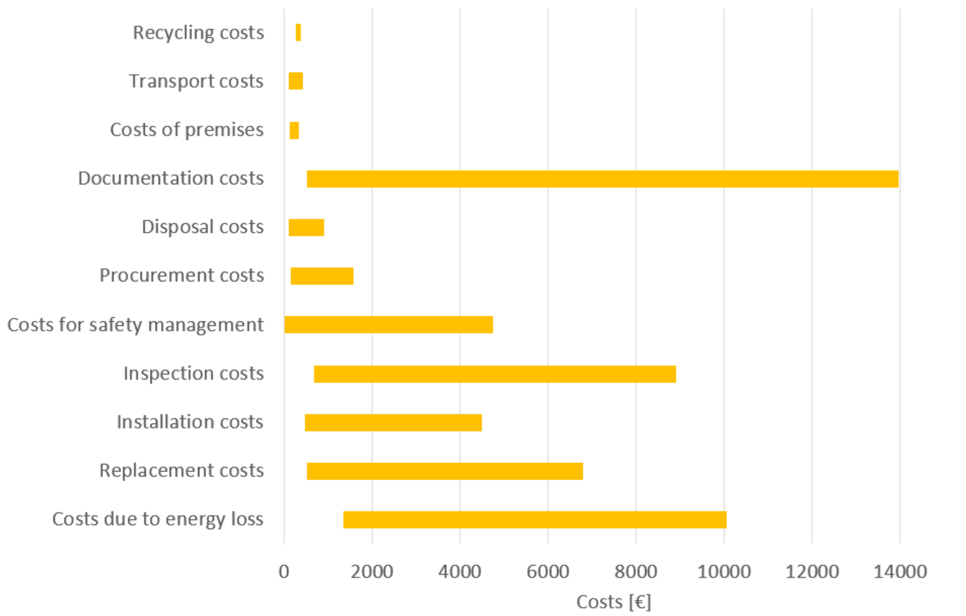


Figure 24: Range of cost factors for an observation period of 40 years. GIS C4-PFN

(24a) All cost factors

(24b) Zoom in cost factors with smaller contributions.

GIS - gas-insulated switchgear
C4-PFN - perfluoronitrile

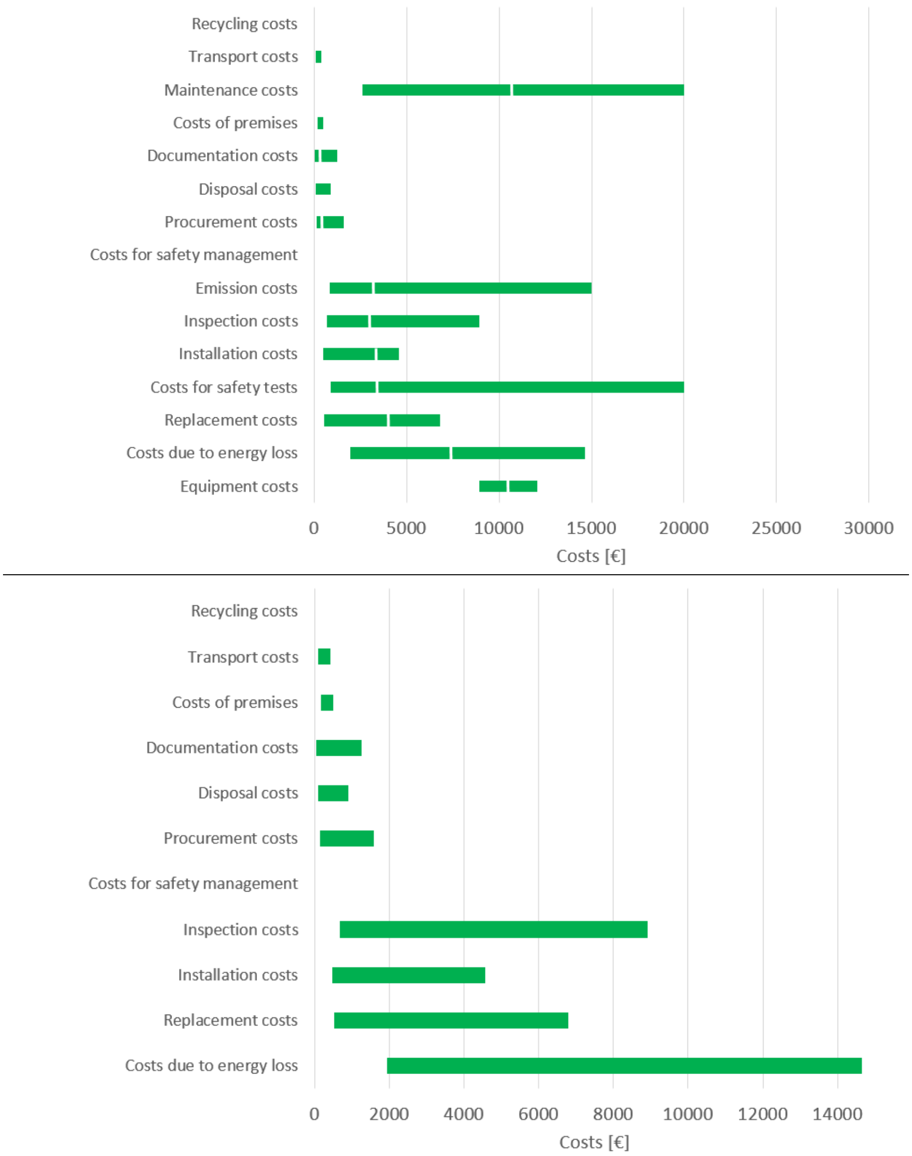
For C5-PFK and C4-PFN, documentation requirements have been considered according to SF_6 because of the fluorine gas content.

Figure 25: Range of cost factors for an observation period of 40 years. AIS

(25a) All cost factors

(25b) Zoom in cost factors with smaller contributions.

AIS - air-insulated switchgear



3.3 Losses during the period under review.

The losses can be divided into 2 areas, the direct monetary costs and the environmental impact, here represented by CO_2 equivalents.

The monetary part consists of the cost factors "costs due to energy loss" and the "emission costs" and represents the priced losses of electrical energy, as well as climate-impacting emissions from insulating gases and the emission factor for the power plant park and are therefore already part of the earlier chapters.

In the case of the environmental impacts, the CO_2 equivalents of the insulating gas losses have a direct effect, while the electrical losses enter via emission factor of the power plant park, for the current electricity mix. For the electrical losses, the technology gas-insulated or air-insulated results in decisive differences. The additional contact resistances caused by the structure of the air-insulated switchgears increase the

losses compared to the gas-insulated switchgears. Due to the different insulating gases, no changes in losses are seen outside the range used.
The prices of CO_2 certificates, on the other hand, are the same for all technologies. Therefore, the CO_2 equivalents that have to be compensated via CO_2 certificates are considered directly at this point.

Figure 26 shows the losses as CO_2 equivalents for the observation period of 40 years as a bar chart, subdivided according to their origin from electrical and insulation gas losses.
For the electrical losses of the GIS, manufacturer data and a study from the University of Southeast Norway [21] were used and extrapolated for the AIS using the life cycle assessment study [1]. The reference value and bandwidth are given in Table 1.
Insulating gas losses due to leakage over the observation period were assumed to be 0.1% per year according to the IEC 62271-1 standard [17]. The range of insulating gas losses at the end of life was based on the LCA study [1] and the study on the development of SF_6 quantities in the European medium-voltage grid inventory [2]. This results in a range of 1.5% to 10%; 2% was used as the reference value.

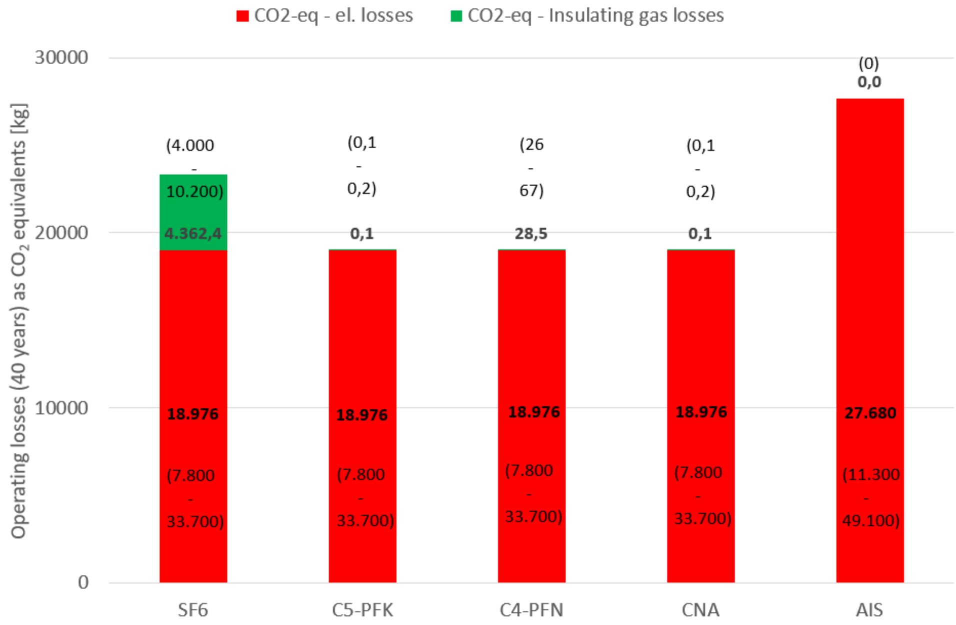


Figure 26: Operating losses as CO2 equivalents.
The reference values as bars and the minimum and maximum values in parentheses.

SF_6 - Sulfur hexafluoride
CNA - Components of Natural Air
C5-PFK - perfluoroketone

C4-PFN - perfluorniteril

For the observation period with the reference values used, the electrical losses are dominant for all switchgear types. Taking into account the bandwidths for the loss energy and the emission factor for the electricity mix, approx. 7,800 - 33,700 kg CO_2 equivalents for the GIS. For all alternatives to SF_6 used, CO_2 equivalents from insulation gas emissions are very low. The relation between CO_2 equivalents from electrical losses and from insulation gas emissions changes with changes in the conversion factor of how many grams of CO_2 equivalents are released per kilowatt hour. In the coming decades, these emissions are to be reduced from the current average of approx. 400 g/kWh to 0 g/kWh for Germany, in line with the target of climate neutrality [22, 23].

In Europe, there is a wide range for this conversion factor, according to published data of the EEA [15], the factor ranges from approx. 10 g/kWh to approx. 900 g/kWh (the reference value used is 400 g/kWh). With further expansion of renewable energy sources, the factor will be reduced and the electrical losses will cause a lower contribution.

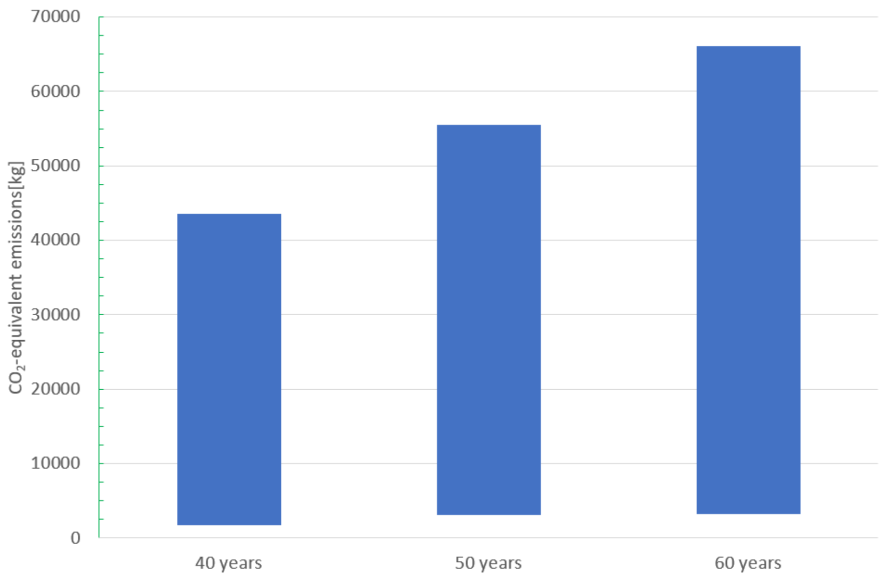
Sensitivity analysis

Using the example of a GIS CNA, Figure 27 shows the range of total CO_2 equivalents generated by losses during operation when the observation period and the conversion factor are changed. For very low conversion factors in the provision of electrical energy, as in Iceland, Sweden or Norway, CO_2 equivalents are mainly generated over the observation period from the rucksack of production and, in the case of SF_6, from the escape of the insulating gases. For the GIS with CNA shown, assuming a continuous current load of 50% of the nominal current, approximately 1,700 kg of CO_2 equivalents are produced within 40 years and at approximately 10 g/kWh, taking recycling into account. This is less than half the CO_2 equivalents due to losses of SF_6. In countries with a conversion factor of about 900 g/kWh, the same switchgear and otherwise the same conditions would produce about 42,000 kg of CO_2 equivalents, which is about 10 times the CO_2 equivalents due to SF_6. By changing the electricity mix, the share of environmental pollution from escaping SF_6 will increase from a negligible 10%, or about 20% for today's electricity mix in Germany, to a dominating 71% for a switchgear system.

Figure 27: CO2 equivalents as a function of the observation period for the conversion factors available in Europe for a GIS CNA type switchgear.

GIS - gas-insulated switchgear

CNA - Components of Natural Air



4
Results

In this study, parameters and cost factors for switchgear were identified and value ranges, through literature research and expert interviews, were determined that occur within their life cycle. An average switchgear was determined from proportions of primary and secondary switchgear panels according to their occurrence in the electrical distribution networks in Germany and the cost factors were calculated for this configuration.

The influence of the individual cost factors was considered for system types, air-insulated, gas-insulated, insulating gases with or without F-gas proportions. The costs for safety tests, equipment costs, costs due to lost energy, were identified as cost factors with large contribution to the overall costs of such switchgears.

For all types of switchgears, the following cost factors are assumed to be the same: "procurement" (procurement process), "transport", "replacement", "safety tests", "disposal" and "inspection".
The cost factors "cost due to energy loss" and "cost of premises" are assumed to be the same for the gas-insulated switchgear types.
Therefore, these cost factors can be neglected for the comparison of the switchgear types.

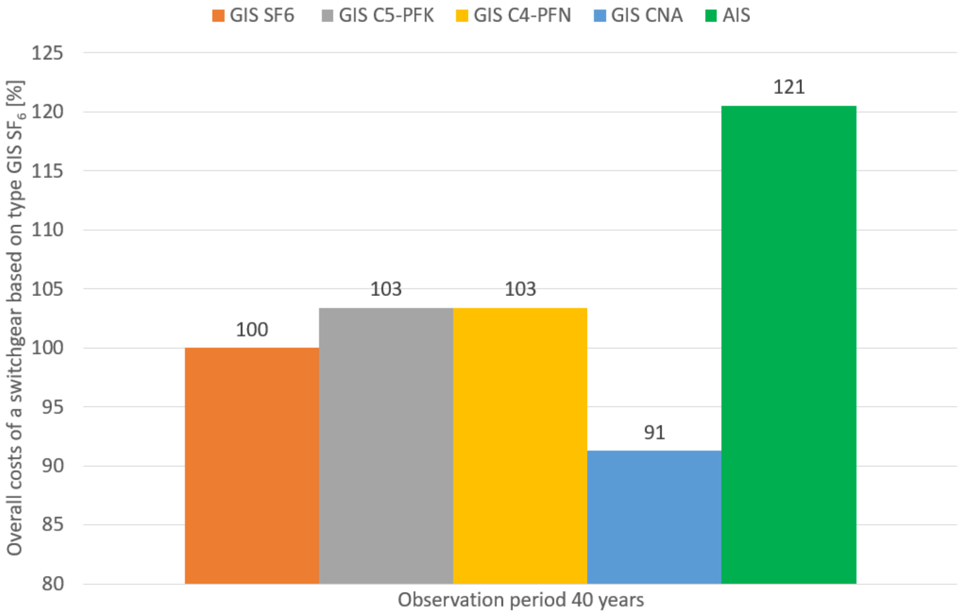


Figure 28: Total costs by switchgear type for the 40-year observation period.

GIS - gas-insulated switchgear
AIS - air-insulated switchgear
SF_6- sulfur hexafluoride
CNA - Components of Natural Air
C5-PFK - perfluoroketone
C4-PFN - perfluoronitrile

For C5-PFK and C4-PFN, the documentation requirements corresponding to SF6 have been taken into account due to the fluorine gas content.

For the gas-insulated switchgears, the cost factors, the costs for the "equipment", the "emissions", the "recycling" of the insulating gas, the "safety management" for insulating gases and the "documentation" are different, shown in Figure 29. These differences result from the different insulating gases and the necessary different measures, from their climate impact and toxicity of their components.
While switchgears with SF_6 as the established technology are more favorable in terms of equipment costs, switchgears with CNA as the insulating gas in particular have an advantage in terms of emission costs, recycling costs, costs for safety management and documentation costs.

Under the assumptions and expenses considered, the two cost factors "costs for safety management" and, significantly, "documentation costs" make F-gas-containing insulating gases more expensive in particular.

Figure 29: Cost factors that are different for GIS switchgear.
GIS - gas insulated switchgear
AIS - air insulated switchgear
SF_6 - sulfur hexafluoride
CNA - Components of Natural Air
C5-PFK - perfluoroketone
C4-PFN - perfluoronitrile

For C5-PFK and C4-PFN, the documentation requirements according to SF_6 are taken into account due to the fluorine gas content.

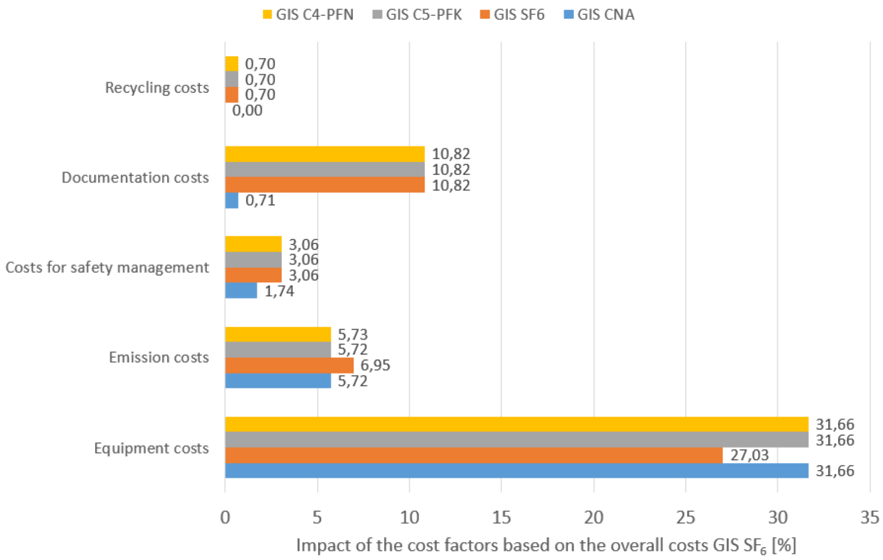


Figure 30: Type-specific cost differences

GIS - gas-insulated switchgear
SF_6 - Sulfur hexafluoride
CNA - Components of Natural Air
C5-PFK - perfluoroketone
C4-PFN - perfluoronitrile

For C5-PFK and C4-PFN, the documentation requirements according to SF_6 are taken into account due to the fluorine gas content.

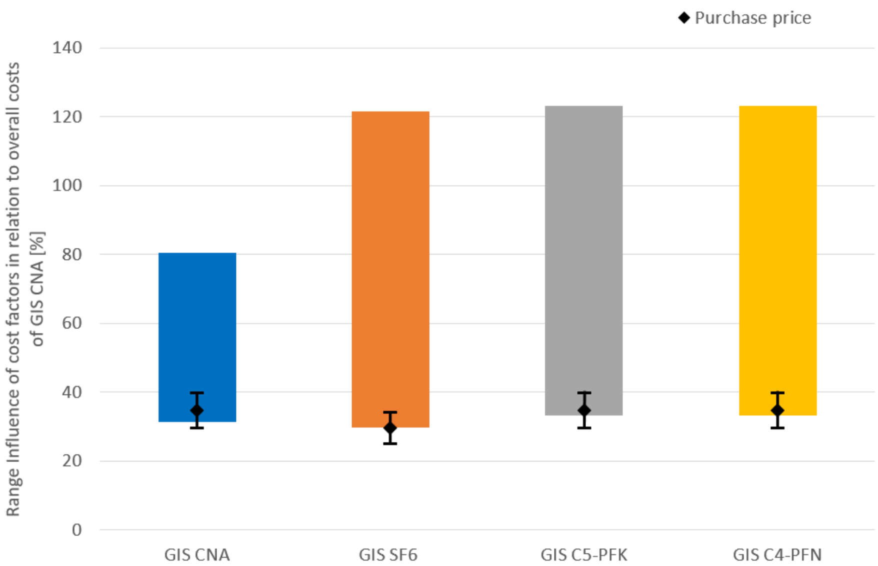


Figure 30 summarizes the cost factors, which are different for GIS switchgears, and shows their range.
Due to the fact that CNA is free of F-gases, there are no "recycling costs" for F-gases and the effort for documentation and safety management for the insulating gas is lower. This reduces the contribution of each cost factor to the total cost with their corresponding ranges.
Cost factors such as "documentation costs" and "costs for safety management" for insulating gases are strongly dependent on national and international requirements with regard to environmental protection and occupational safety and could change significantly in the future. Particularly in view of the discussions on climate change, increasing expenditure and thus rising costs can be expected for gases with a strong impact on the climate.

Compared to the gas-insulated switchgear types, maintenance costs take the position as the largest cost factor for the air-insulated switchgear. In addition, the contributions from "energy loss" and "emissions" are significantly larger than for the gas-insulated switchgear.
In contrast, the costs for "safety management for insulating gases" and for "documentation of insulating gases containing fluorine gas" are significantly lower for the AIS.

There is a great deal of uncertainty for the price of CO_2 certificates, which are highly dependent on political and economic objectives. In view of the current developments for more climate protection, a stronger price increase can be assumed. In addition to the price of the CO_2 certificates, the electricity mix is of great importance for the emission costs; the less CO_2 released per kWh, the lower the emission costs and the environmental impact. Already today, in some countries, due to their electricity mix, the share of emission costs is significantly lower than the values shown using the electricity mix in Germany.

With regard to the recycling of alternative insulating gases containing F-gas, there is still uncertainty about the costs due to a lack of empirical values. At present, there is no experience with regard to possible impurities and degrees of impurity in the gases that are recycled. Suppliers for corresponding recycling so far assume comparable costs to SF_6.

The study shows economic advantages and disadvantages of the considered technologies, the most important cost factors and their ranges in order to enable an economic and environmentally friendly optimization.

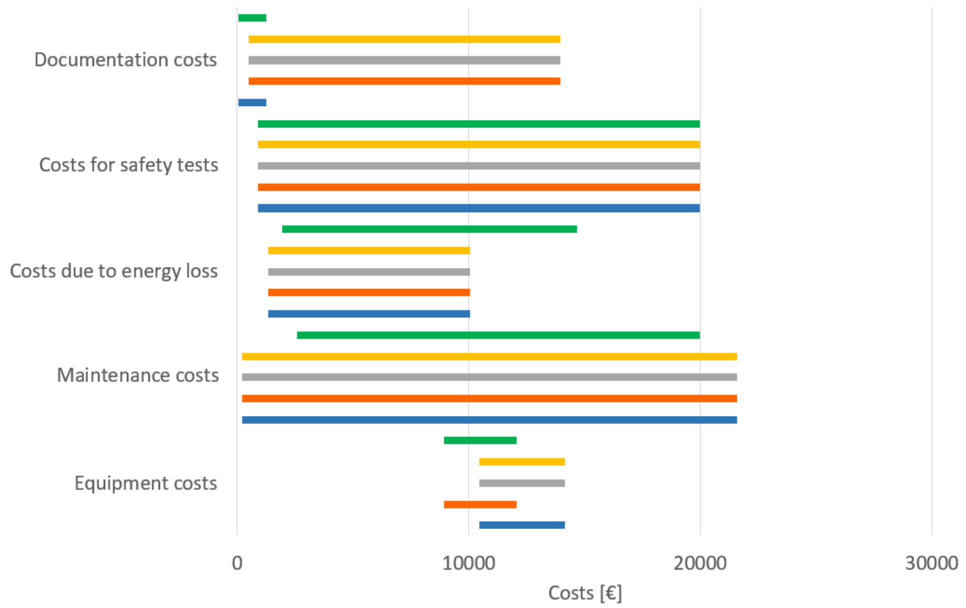


Figure 31: Range of cost factors with the largest share of overall costs for the reference values.
GIS - gas-insulated switchgear
AIS - air-insulated switchgear (green)
SF_6 - sulfur hexafluoride (orange)
CNA - Components of Natural Air (blue)
C5-PFK - perfluoroketone (gray)
C4-PFN - Perfluoronitrile (yellow)

In the case of C5-PFK and C4-PFN, the documentation requirements corresponding to SF6 have been taken into account due to the fluorine gas content.

5 Abbreviations

AIS	Air insulated switchgear (AIS)
EEA	European Environment Agency
EU	European Union
F-Gas	Fluorine-containing gas
C5-PFK	Perfluoroketone
C4-PFN	Perfluoronitrile
CNA	Components of Natural Air
GIS	Gas insulated switchgear
ICLEI	Local Governments for Sustainability
RMU	Ring cable switchgear
SF_6	Sulfur hexafluoride

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7 Annex

Assumed scenarios for the price development of CO_2 certificates

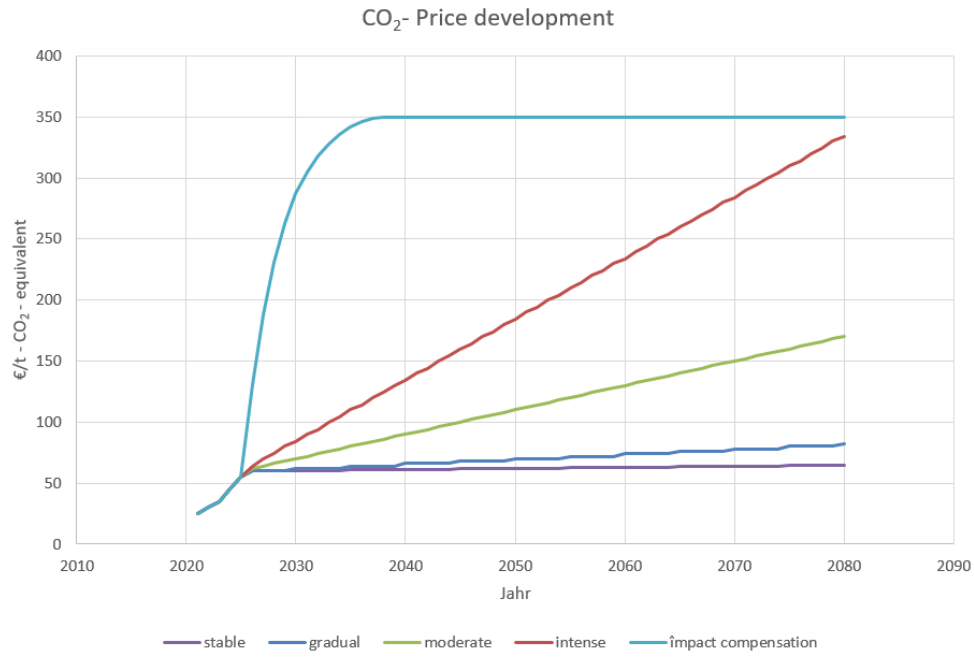

Figure 32: Scenarios for the price development of CO_2 certificates

Release of the insulation gases

	GIS SF_6	GIS C5-PFK	GIS C4-PGN	GIS CNA	AIS
€ (55 €/t)	4.094	0,07	26	0,07	0
€ (350 €/t)	26.052	0,41	168	0,41	0
kg CO_2-equivalent	74.435	1,2	481	1,2	0

Table 3: Release of insulating gases potential cost or burden on the environment in CO_2 equivalent

When the environmental impact from the release of the insulating gas is compared, as in Table 3, the potential impact is significantly greater for SF_6 than for the alternative insulation options. The table is based on the gas volume used for the hypothetical switchgear system in the study. The same value is used for CNA and C5-PFK, both with a climate impact of <1.
A release can occur due to improper handling in the form of mechanical damage, or due to energetic damage such as electrical faults in the switchgear area. For Germany, the VDE FNN recorded approximately 360 faults with damage to medium-voltage level switchgear in the 2017 fault statistics, of which approximately 250 were in the secondary distribution level [24].
The toxic properties of C5-PFK and C4-PFN [10] pose yet another potential hazard for this.

Range of type-specific cost factors

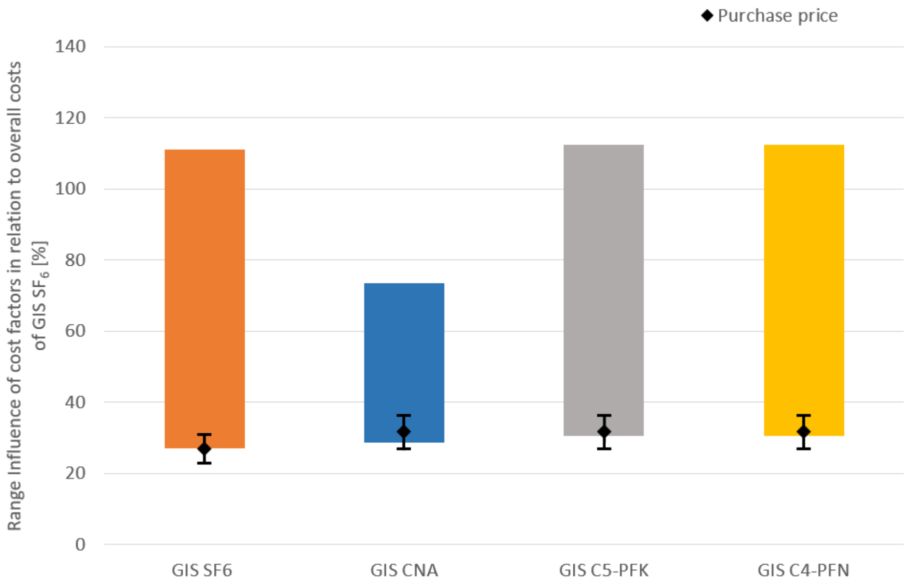

Figure 33: Range of type-specific cost factors related to the overall cost of the GIS CNA system.

GIS - gas-insulated switchgear
SF_6 - Sulfur hexafluoride
CNA - Components of Natural Air
C5-PFK - perfluoroketone
C4-PFN - perfluoronitrile

For C5-PFK and C4-PFN, the documentation requirements corresponding to SF_6 have been taken into account due to the fluorine gas content.

Ranking of cost factors (observation period 40 years)

Cost factor	GIS CNA	GIS SF_6	GIS C5-PFK	GIS C4-PFN	AIS
Equipment costs	1	1	1	1	2
Procurement costs	9	10	10	10	9
Documentation costs	11	3	3	3	12
Emission costs	7	8	8	8	7
Disposal costs	10	11	11	11	11
Installation costs	5	7	7	7	6
Inspection costs	6	7	7	7	7
Costs due to energy loss	2	2	2	2	3
Replacement costs	3	4	4	4	4
Costs of premises	12	13	13	13	10
Cost of safety management	8	9	9	9	-
Cost of safety tests	4	5	5	5	5
Recycling costs F-gas	-	12	12	12	-
Transport costs	14	15	15	15	13
Maintenance costs	13	14	14	14	1

Data base EEA (2019) Conversion factors

MV_GIS	Comment / Explanation	Unit	kg CO_2/un	Electricity?
000_FUEL_TYPES	Upstream fuel emissions are based on Germany			
001_wood-pellets	upstream emissions	kg	0,059923	no
002_wood-chips	upstream emissions	kg	0,023022	no
003_bioethanol	upstream emissions	liter	1,517186	no
004_biodiesel_rapeseed	upstream emissions	liter	2,617942	no
005_biodiesel_rapeseed_organic	upstream emissions	liter	2,617942	no
006_biodiesel_rapemethylester	upstream emissions	liter	2,611115	no
007_biodiesel_sunflowerseed-oil	upstream emissions	liter	2,612771	no
008_biodiesel_soymethylester	upstream emissions	liter	2,611175	no
009_biodiesel_palmoil	upstream emissions	liter	2,611253	no
010_fossile-oil_lite	incl. upstream emissions, efficiency = 100%	liter	2,667165	no
011_natural-gas_cooking	incl. upstream emissions, efficiency = 100%	kWh	0,281626	no
012_natural-gas_heating	incl. upstream emissions, efficiency = 100%	kWh	0,2519	no
013_CNG_compressed-natural-gas	incl. upstream emissions, efficiency = 100%	kg	3,212786	no
014_fossile-oil_lite_heating	incl. upstream emissions, efficiency = 100%	liter	3,188514	no
015_liquid-gas	incl. upstream emissions, efficiency = 100%	kWh	0,2774	no
016_diesel	incl. upstream emissions, efficiency = 100%	liter	3,08896	no
017_petrol	incl. upstream emissions, efficiency = 100%	liter	2,91931	no
018_lignite-briquettes_high-quality	incl. upstream emissions, efficiency = 100%	kg	2,051513	no
019_lignite-briquettes_low-quality	incl. upstream emissions, efficiency = 100%	kg	2,554258	no
020_coal-briquettes	incl. upstream emissions, efficiency = 100%	kg	3,713315	no
021_coke	incl. upstream emissions, efficiency = 100%	kg	2,978627	no
023_AT_electricity-mix_incl-grid	Austria	kWh	0,091	yes
024_BE_electricity-mix_incl-grid	Belgium	kWh	0,167	yes
025_BG_electricity-mix_incl-grid	Bulgaria	kWh	0,421	yes
026_CH_electricity-mix_incl-grid	Switzerland	kWh	0,029	yes
027_CY_electricity-mix_incl-grid	Cyprus	kWh	0,651	yes
028_CZ_electricity-mix_incl-grid	Czech Republic	kWh	0,431	yes
029_DE_electricity-mix_incl-grid	Germany	kWh	0,338	yes
030_DK_electricity-mix_incl-grid	Denmark	kWh	0,126	yes
031_EE_electricity-mix_incl-grid	Estonia	kWh	0,891	yes
032_ES_electricity-mix_incl-grid	Spain	kWh	0,207	yes
033_FI_electricity-mix_incl-grid	Finland	kWh	0,086	yes
034_FR_electricity-mix_incl-grid	France	kWh	0,052	yes
035_GB_electricity-mix_incl-grid	United Kingdom	kWh	0,228	yes
036_GR_electricity-mix_incl-grid	Greece	kWh	0,589	yes
037_HU_electricity-mix_incl-grid	Hungary	kWh	0,212	yes
038_IE_electricity-mix_incl-grid	Ireland	kWh	0,316	yes
039_IT_electricity-mix_incl-grid	Italy	kWh	0,233	yes
040_LT_electricity-mix_incl-grid	Lithuania	kWh	0,022	yes
041_LU_electricity-mix_incl-grid	Luxembourg	kWh	0,074	yes
042_LV_electricity-mix_incl-grid	Latvia	kWh	0,117	yes
043_MT_electricity-mix_incl-grid	Malta	kWh	0,357	yes
044_NL_electricity-mix_incl-grid	Netherlands	kWh	0,39	yes
045_NO_electricity-mix_incl-grid	Norway	kWh	0,019	yes
046_PL_electricity-mix_incl-grid	Poland	kWh	0,719	yes
047_PT_electricity-mix_incl-grid	Portugal	kWh	0,244	yes
048_RO_electricity-mix_incl-grid	Romania	kWh	0,293	yes
049_SE_electricity-mix_incl-grid	Sweden	kWh	0,008	yes
050_SI_electricity-mix_incl-grid	Slovenia	kWh	0,231	yes
051_SK_electricity-mix_incl-grid	Slovakia	kWh	0,114	yes
052_SF6		kg	22800	no

Minimum overall costs:

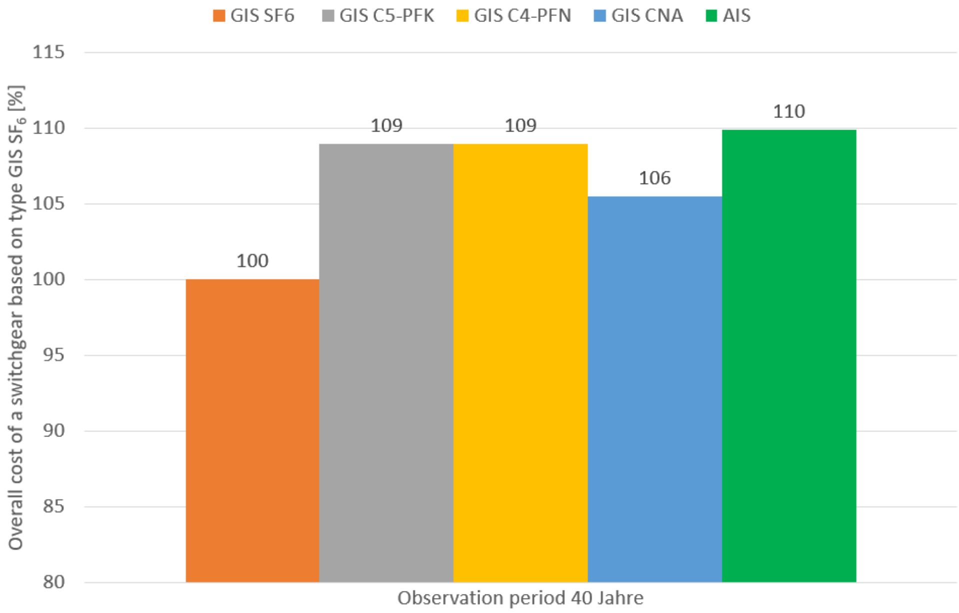

Figure 34: Overall costs by switchgear type for the observation period of 40 years, taking into account the minimum parameter values.

GIS - gas-insulated switchgear
AIS - air-insulated switchgear
SF_6 - sulfur hexafluoride
CNA - Components of Natural Air
C5-PFK - perfluoroketone
C4-PFN - perfluoronitrile

For C5-PFK and C4-PFN, the documentation requirements corresponding to SF6 have been taken into account due to the fluorine gas content.

Data on environmental influences of different manufacturers

Finally, the other environmental influences are considered, with the aim of being able to compare the different technologies. For this purpose, data from manufacturers' life cycle analyses are used, as well as data that can be found in the literature [1]. The environmental impacts are divided into eutrophication potential EP, greenhouse gas potential GWP (Global Warming Potential), acidification potential AP (Acid potential), ozone creation potential POCP (Photochemical Ozone Creation Potential) and ozone depletion potential ODP (Ozone Depletion Potential).

		Switch-gear 1	Switch-gear 2	Switch-gear 3	Switch-gear4	Switch-gear 5
EP	kg PO_4^{3-}	1,09	29,7	0,087	3,593	3,695
GWP	kg CO_2	1550	998	1870	1951	1973
AP	kg SO_2	15,56	46,76	-	44,03	43,84
POCP	kg C_2H_4	1,01	18,6	0,575	-	-
ODP	kg CFC	0,001	0,009	0,001	-	-

Table 4: Data on environmental impacts of switchgear from various manufacturers.
EP - Eutrophication potential
GWP - greenhouse gas potential
AP - acidification potential
POCP – photochemical ozone creation potential
ODP - ozone depletion potential

Databases and tools such as GABI or EIME are used to determine the data in life cycle analyses. These databases provide information on various resources and processes and can thus be used to create a life cycle analysis for LCAs. In Table 4, data from LCAs of different manufacturers on comparable switchgears are presented. Some environmental impacts are shown in comparable ratios to each other, indicating similar quantities and processes, while others show very large deviations.
Deviations generally indicate different quantity structures and/or processes. Since not all details are published, it is not possible to understand what accounts for the

respective significant differences. Thus, a comparison of different types of switchgears with different insulation gases, especially if some solutions are manufacturer-specific, is not meaningful based on the available data. Different preconditions and assumptions lead to very different results, which do not allow any statements to be made about the respective switchgear types. For further utilization of the data, a good insight into the preparation of the respective life cycle analysis is required. This is the only way to avoid comparing figures that are based on different assumptions.
Since different assumptions can have a significant influence on the calculated values, we refrain from further processing of the data in order to avoid false conclusions. In order to avoid mixing switchgear type specific values with manufacturing process specific values.

Only a uniform process, where the different assumptions are comparable, can provide comparable values on environmental impacts of the switchgear types. This could be realized by input quantities (energy consumption, material quantities, etc.) multiplied by defined characteristic values. Manufacturers could provide corresponding data to independent bodies that determine reference values.

Costs of downtimes

The failure of switchgear can cause very large financial costs. This can include penalties, lost profits due to lost production, labor costs without corresponding work, or cleaning and restarting of equipment. The respective points are strongly dependent on the operator and the affected switchgear and the connected plants.
In case of plannable failure or unavailability of switchgears, the costs can be optimized organizationally. The avoidance of all costs cannot always be guaranteed, which is why the possible costs for network operators in the case of cyclical unavailability are shown here. According to Table 1, the times and costs for the unavailability of the switchgear considered in this study are taken into account.
Since the times and costs are comparable according to the statements of the expert interviews for the technologies considered, the costs for downtime maintenance and costs for downtime safety testing are considered to be the same for the switchgear types in this calculation. The costs for the observation period of 40 years are shown in Table 5.

Table 5: Imputed costs in case of actual unavailability of the considered average switchgear in observation period of 40 years.
GIS - gas-insulated switchgear

CNA - Components of Natural Air

	Costs (over 40 years)	Ratio to the overall costs
Downtime maintenance costs	176.000 €	401% GIS CNA
Costs for downtime safety tests	70.400 €	160% GIS CNA

In relation to the total costs of a gas-insulated switchgear with CNA in the same observation period, it becomes apparent how important it is to avoid corresponding costs. These cost factors can be significantly higher than the overall costs for the switchgear, regardless of the technology used.