

# Life Cycle Assessment of Different Concepts of SF<sub>6</sub>-free Gas Insulated Switchgear



Sulphur hexafluoride (SF<sub>6</sub>) is the world's most potent greenhouse gas known today and has a global warming potential (GWP) of 25,200 over a 100-year period. Its concentration in the atmosphere continues to increase in abundance.

**“SF<sub>6</sub>, used in electrical distribution systems, magnesium production, and semi-conductor manufacturing, increased from 7.3 ppt in 2011 to 10.0 ppt in 2019 (+36%). Alternatives to SF<sub>6</sub> or SF<sub>6</sub>-free equipment for electrical systems have become available in recent years, but SF<sub>6</sub> is still widely in use in electrical switchgear.”<sup>9</sup> [IPCC\_AR6\_WGI\_Chapter 02]**

In this situation, with market ready and reliable alternatives existing, regulatory changes by policy makers as well as changes in equipment specifications by utilities and industry are demanded. This study sets focus on the high voltage gas insulated switchgear (GIS) with rated voltage up to 145 kV. Whilst SF<sub>6</sub> is causing the largest share of climate impact if used in this type of electrical equipment, it is not the only relevant contributor. For instance, GIS is typically made of aluminium to a large extent. Furthermore, even with a climate emergency at hand, global warming potential is not the only relevant environmental impact category to be considered. Therefore, a holistic assessment of SF<sub>6</sub> alternatives is required to support decision makers. This assessment can be provided best within the principles and framework of life cycle assessment, ISO 14040. Within this study, SF<sub>6</sub> and two available alternative technologies are assessed side by side using this framework.

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## List of acronyms

ADP	Abiotic Depletion Potential
AP	Acidification Potential
CML	Centre of Environmental Science at Leiden
ELCD	European Life Cycle Database
EoL	End-of-Life
EP	Eutrophication Potential
FU	Functional unit
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
ILCD	International Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NMVOC	Non-Methane Volatile Organic Compound
ODP	Ozone Depletion Potential
POCP	Photochemical Ozone Creation Potential
SFP	Smog Formation Potential
VOC	Volatile Organic Compound

# Contents

<b>1</b>	<b>Introduction .....</b>	<b>5</b>
1.1	LCA methodology overview .....	5
<b>2</b>	<b>Goal and scope.....</b>	<b>7</b>
2.1	Goal and description of study .....	7
2.2	Scope of study .....	7
2.2.1	Product system.....	7
2.2.2	Product Function and Functional Unit (FU) .....	8
2.2.3	System boundaries.....	9
2.2.4	Data Quality Requirements .....	10
2.2.5	Assumption and Limitations.....	10
2.2.6	Scenarios.....	12
2.2.7	Allocation .....	13
2.2.8	Cut-off Criteria .....	14
2.2.9	Type and Format of the Report.....	14
2.2.10	Software and Database .....	14
2.2.11	Critical Review.....	14
<b>3</b>	<b>Life cycle inventory analysis.....</b>	<b>15</b>
3.1	Data collection procedure .....	15
3.2	Product System GIS ELK-04, 145 kV .....	15
3.2.1	Overview of Product System .....	15
3.2.2	Component Transport.....	16
3.2.3	Production .....	16
3.2.4	Transport to customers.....	17
3.2.5	Use Phase .....	17
3.2.6	End-of-Life .....	18
3.3	Background Data .....	18
3.3.1	Fuel and Energy .....	18
3.3.2	Key Raw Materials and Processes .....	18
3.3.3	Transportation .....	19
<b>4</b>	<b>Life cycle impact assessment.....</b>	<b>20</b>
4.1	Environmental Impact Categories and Interpretation approach .....	20
4.1.1	Selection of LCIA Methodology and Impact Categories .....	20
4.1.2	Interpretation approach .....	22
4.2	ELK-04, 145kV GIS design options LCA - Results .....	23
4.2.1	Comparison between option 1 and option 2 .....	23
4.3	Comparative scenario overview .....	24
4.4	Modelling Aluminium with the EC PEF Circular Footprint Formula .....	32
<b>5</b>	<b>Life cycle interpretation .....</b>	<b>35</b>
5.1	Data Quality Assessment .....	35
5.1.1	Precision and Completeness.....	35
5.1.2	Consistency and Reproducibility .....	35
5.1.3	Representativeness.....	35
5.2	Model Completeness and Consistency .....	35
5.2.1	Completeness.....	35
5.2.2	Consistency .....	36
5.3	Conclusions. Limitations. and Recommendations .....	36
5.3.1	Conclusions.....	36
5.3.2	Recommendations.....	36
<b>6</b>	<b>References .....</b>	<b>37</b>

# 1 Introduction

## 1.1 LCA methodology overview

Life cycle assessment provides a holistic view on the environmental impact of the alternative solutions, giving insight to the key drivers of environmental impact for each technology and providing business decision support moving forward. Life cycle assessments (LCA) investigate the environmental impacts related to a product or a product system during the complete product or product system life cycle. This includes evaluating energy and resource consumption as well as emissions from all life cycle stages including material production, manufacturing, use and maintenance and End-of-Life.

An LCA is divided into four phases. In accordance with the current terminology of the International Organization for Standardization (ISO), the phases are called goal and scope definition, inventory analysis, impact assessment, and interpretation, as Figure 1 illustrates.

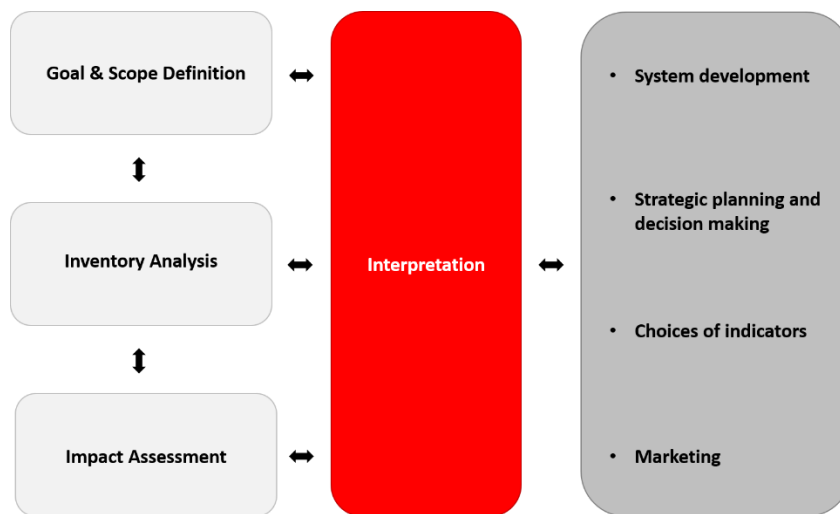


Figure 1. Illustration of the LCA system.

An LCA identifies, quantifies, and assesses sources of environmental impact throughout a product's life cycle. An LCA helps prioritize how to make improvements on processes or products.

In terms of methodology, an LCA could be meant with different scopes depending on the phases it is intended to cover. Those different scopes are listed hereafter:

- **Cradle to Gate:** in this type of LCA, the assessment is performed from the raw material extraction to product leaving the factory ready for distribution, covering also material processing and product manufacturing.
- **Cradle to Grave:** in this type of LCA, the assessment is performed from the raw material extraction to the End-of-Life of the product, covering all the intermediate phases and leaving out of scope the recycling of materials when the product is disposed.
- **Cradle to Cradle:** in this type of LCA, the assessment is performed from the raw material extraction to the re-use of recycled material after product disposal, covering all the intermediate phases.



Figure 2. LCA stages and scope.

## 2 Goal and scope

### 2.1 Goal and description of study

Sulphur hexafluoride (SF<sub>6</sub>), used in high-voltage electrical equipment like gas insulated switchgear, as insulating and extinguishing medium, is so far, the most potent greenhouse gas known with a lifetime of 3 200 years and global warming potential GWP100 of 25 200 (AR6, IPCC assessment report)<sup>10</sup>. In recent years, several alternative concepts have evolved on how to replace SF<sub>6</sub> in gas insulated switchgear by alternative insulation and extinguishing media, most prominent mixtures containing (CF<sub>3</sub>)<sub>2</sub>CFCN and CO<sub>2</sub> and technical air. (CF<sub>3</sub>)<sub>2</sub>CFC itself has a GWP of 2 750 but its concentrations in mixtures is usually well below 10% vol.

Within this study, the environmental performance of products designed based on these two concepts shall be assessed. As SF<sub>6</sub> cannot be replaced by alternative media one to one, but major redesign of the product is needed, this shall be done in a comprehensive way, where not only the environmental impact of the gas is to be considered but all inventory data of the products creating an environmental impact.

This study shall support a decision whether not only SF<sub>6</sub> shall be banned from usage in gas insulated switchgear but also all other insulation media with a significant global warming potential. It is addressed to policy makers, utilities generating, transmitting, and distributing electrical energy and other industries using gas insulated switchgear.

This study complies with ISO 14040:2006 (Environmental management - Life cycle assessment - Principles and framework)<sup>6</sup> and ISO 14044: 2006 (Environmental management - Life cycle assessment - Requirements and guidelines)<sup>7</sup>. It has been verified by IVL, Swedish Environmental Research Institute and is commissioned by Hitachi Energy Ltd.

### 2.2 Scope of study

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

#### 2.2.1 Product system

Gas insulated high voltage switchgear (GIS)<sup>4</sup> is a compact metal encapsulated switchgear consisting of high-voltage components such as circuit breakers and disconnectors. The main function of a GIS substation is to provide short circuit breaking, switching, measuring, and earthing possibilities for the high-voltage grid on both, transmission, and distribution level. Compared to other types of switchgear and devices, like air insulated switchgear, GIS are at favor where space is limited, high reliability and low maintenance effort is required, severe environmental conditions are present and where aesthetic qualities take precedence.

The metal encapsulation is usually made from Aluminium and designed either as cast or welded structures. This material is used to avoid undue heating close to high AC currents. Electric potential of the encapsulation is ground level. The insulation between encapsulation and conductors and – in case all three phases are in the same enclosure – between the conductors is ensured by an insulation gas at a pressure level usually a factor 5 to 10 above atmospheric pressure. In conventional GIS this gas is SF<sub>6</sub>. In case a nominal or even a short circuit current must be interrupted, an electric arc appears between the open contacts. The hot gas created by this arc will be blown away and replaced by SF<sub>6</sub>. Therefore, this gas has two functions, insulation and arc extinction.

GIS are designed in a modular way, that its different functions are realized in different kinds of modules. As the interface between modules of one product is standardized, those modules can be combined in a flexible way to realize the electrical scheme specified by customer. Main types of modules are listed hereafter.

- Circuit breaker. Breaks nominal or short circuit currents and makes the connection between two segments of the grid even if they are on a different voltage level initially.

- Disconnectors. Separates devices safely from high potential, e.g., to allow maintenance. Can be combined with earthing switches.
- Earthing switches. Connects conductors to ground to allow safe maintenance. Make proof earthing switches connect to ground even with residual electrical energy stored in the system.
- Instrument transformers. Measurement of voltage and current for metering and protection purposes.
- Interface modules. Connect to other elements of high voltage grid, cables, overhead lines, or transformers

Local control cubicles contain elements to control, protect, interlock, and monitor primary devices. Other elements which are used less frequently and not in the scope of this study like surge arresters and connecting elements like bus ducts. Furthermore, their composition of inventory is either a very similar to the modules in scope or not significantly impacted by the choice of insulation medium. Therefore, the unit as described below is suitable to achieve the goal of this study.

### 2.2.2 Product Function and Functional Unit (FU)

The reference functional unit of the study chosen is one bay of ELK-04, 145 kV. Substations usually consist of several such bays arranged along a bus bar. They can have different functionalities like feeding, distributing or metering of energy. Within each bay, modules are arranged in different layouts to fulfil customer needs. The number of bays can vary between one (simple line in, line out bay) and up to the range of 20 and above. A very typical bay layout in the range up to 145 kV is a so-called double-busbar-bay. It consists of a circuit breaker, two disconnectors and earthing switches on the bus bar side and on the exit side a cable connection with disconnector, earthing switches and measuring devices for voltage and current. This type of bay was chosen here as reference unit. The unit contains primary equipment (modules as described before), secondary equipment (local control cubicle and bay wiring) and supporting steel structure. The size of a GIS is – in a simplified description – defined by three dimensioning criteria. Firstly, rated voltage defines the necessary insulation (geometrical distance and pressure). Secondly, nominal current defines size of conductors and amounts of gas and surface necessary to transport heat generated by ohmic losses. Thirdly, short circuit current defines energy demand for breaking and mechanical strength to bear magnetic forces. The reference functional unit is designed for a rated voltage up to 145 kV, a rated current range up to 3 150 A and a short circuit current up to 40 kA. These specific voltage and current ratings are typical for GIS products in this voltage range. Temperature range is between -30°C and +70°C. SF<sub>6</sub> is used as insulation and extinction medium.

Two concepts avoiding SF<sub>6</sub> as insulation medium are in scope:

- Option 1: GIS based on ELK-04, 145 kV with same ratings but redesigned using a mixture of (CF<sub>3</sub>)<sub>2</sub>CFCN, CO<sub>2</sub> and O<sub>2</sub> as insulation and extinction medium.
- Option 2: GIS based on ELK-04, 145 kV with same ratings but redesigned using technical air as insulation medium and a vacuum interrupter for arc extinction.

The performance of the GIS was calculated on a 40-year lifetime, with a running time per year of 350 400 hours (24 hr/day).



Table 1. ELK-04, 145 kV components list.

Quantity	Item
1	Circuit breaker including drive
1	Integrated current transformer
3	Disconnecter and earthing switches including drives
1	Make proof earthing switch
1	Voltage transformer
1	Cable end unit
1	Local control cubicle
1	Supporting steel structure



### 2.2.3 System boundaries

The production of the GIS ELK-04, 145 kV is taking place in Zürich, Switzerland. The following stages or phases have been included:

- Manufacturing of components and other material
- Transport of components and other materials from the suppliers to assembly
- Assembly phase
- Transport to customer
- Use phase
- Transport of product to End-of-Life, and
- End-of-Life (EoL) phase or dismantling

Gas leakage was included in the form of losses during the manufacturing, use phase and losses at the time of dismantling (EoL). Most of the metals were regarded as recyclable. Energy and auxiliary materials needed for remelting of metal scrap to secondary materials that substitute primary materials were included in the EoL phase.

Table 2. System boundaries.

Included	Excluded
<ul style="list-style-type: none"> <li>- LCA stages (production, use, EoL)</li> <li>- Transport of materials to production site</li> <li>- Packaging of the product</li> <li>- Transport of the product to customers</li> <li>- Gas leakage and emissions during use phase and EoL</li> <li>- Transport of the product to recycling facility</li> <li>- Recycling of materials</li> </ul>	<ul style="list-style-type: none"> <li>- Construction of major capital equipment (infrastructure)</li> <li>- Maintenance and operation of support equipment</li> <li>- Human labour and employee transport</li> </ul>

### 2.2.3.1 Time Coverage

The data collection process was carried out by Hitachi Energy. As agreed with the client, the study will be conducted based on the material composition of the switchgear. Furthermore, the data collected reflects the year 2022. These results are valid until significant technological changes occur.

### 2.2.3.2 Technology Coverage

With regards to the production, the different technologies assessed in this study:

- Option 0, GIS ELK-04, 145 kV is covered by using real primary data reported from the production site,
- Option 1, GIS ELK-04, 145 kV using alternative insulation gas is covered by using same data as Option 0 plus scaling according to laws of physics,
- Option 2, GIS ELK-04, 145 kV using technical air as insulation gas is covered by using real primary data of the most suitable, but different SF<sub>6</sub>-model range (ELK-04, 170 kV) plus scaling according to laws of physics.

### 2.2.3.3 Geographical Coverage

As primary data is used with regards to the product, the local circumstances (regional grid mixes, fuel mixes, raw material import mixes) should be considered and covered in this study as far as possible.

### 2.2.4 Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under the constraint, that the options are neither designed in detail nor produced with considerable volume.

- Measured primary data are of the highest precision, followed by calculated data, literature data, and estimated data. The goal is to model all relevant foreground processes using measured or calculated primary data for the reference case. The two options, data must be calculated and estimated. However, as both concepts follow similar design rules like a GIS using SF<sub>6</sub>, and as products of different dimensions are available for reference, precision of calculations and estimates is still considered sufficient to reach the goal of this study. The Error margins due to generic datasets are managed in this manner.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data in this regard.
- Consistency refers to modelling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modelling choices, data sources, emission factors, or other artefacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report. The goal is to provide enough transparency with this report so that third parties can approximate the reported results. This ability may be limited by the exclusion of confidential primary data and access to the same background data sources.

### 2.2.5 Assumption and Limitations

As this study is comparing to technological concepts without having details design at hand, some inventories must be estimated based on technologically reasonable assumptions. Based on internal screening assessments carried out by Hitachi Energy, design is more advanced and fewer assumptions are needed for option 1.

When changing from SF<sub>6</sub> to alternative gases, most important properties of the alternative gas to be considered when evaluating the impact on design are:

- insulation properties, which, compared to SF<sub>6</sub>, are weaker for (CF<sub>3</sub>)<sub>2</sub>CFCN and even more so for technical air,
- arc extinguishing or thermal properties, which are not on a relevant level for both, (CF<sub>3</sub>)<sub>2</sub>CFCN and technical air.
- dew point curve

- material compatibility in both ways, chemical resistance of gas against GIS materials, and resistance of GIS materials against gas decomposition products.

The most important design changes stemming from these properties are listed in Table 3. Focus is on those changes which might have an impact on the inventory.

Table 3. Overview of design changes.

Modules	Option 1	Option 2
All	As dew point is above minimum temperature partial pressure of insulation gas must be reduced by mixing with other components. The volume shares considered in this study are 3.5% C <sub>4</sub> -FN, 86.5% CO <sub>2</sub> , 10% O <sub>2</sub> .	Dew point is no issue for technical air.
All	<p>Total gas pressure must be increased to compensate weaker insulation properties, while module dimensions can remain same. Filling pressure is increased from 600 kPa to 880 kPa.</p> <p>An increase of wall thickness can be avoided for cast enclosures if process is changed from sand cast to dye cast due to better material structure and surface</p>	<p>Insulation properties require an increase of both, module dimensions and gas pressure. Flange diameter and basic module dimension are increased from 520 mm / 650 mm (dimensions of SF<sub>6</sub> GIS for 145 kV) to 735 mm / 850 mm (same dimensions as SF<sub>6</sub> GIS for 170 kV).</p> <p>Assumption: With these dimensions, system pressure must be increased from 600 kPa to 790 kPa.</p> <p>Assumption: An increase of wall thickness can be avoided for cast enclosures if process is changed from sand cast to dye cast.</p>
All	<p>Gas leakages depend very much on design and maintenance of the equipment. According to IEC, leakages in type tests must be limited to SF<sub>6</sub> 0.1% / a, in routine tests to 0.5% / a. However, with advanced design and routine testing techniques they can be limited to 0.1% / a even over lifetime in service.</p> <p>Assumption: Due to the lower concentration of traceable gas in C<sub>4</sub> mixture and therefore less sensitivity in routine testing, leakages are assumed to be 0.2%.</p>	There is no direct impact of leakages of technical air on the environment.

Circuit breaker	<p>For arc extinguishing a component with more favourable thermal properties, e.g., CO<sub>2</sub> must be foreseen in the gas mixture. Mixture is the same like for other modules (see above).</p> <p>Due to the insulation properties, gas pressure must be increased from 700 kPa to 880 kPa.</p> <p>Interrupters must move faster. Therefore, a drive with more stored energy is to be used. It is similar to the drive used for SF<sub>6</sub> GIS ELK-04 / 170.</p> <p>Additional exhaust volume must be foreseen. Height of circuit breaker increases by 300 mm.</p>	<p>Due to insulation properties, both dimensions and pressure must be increased.</p> <p>Assumptions: Pressure is increase to 790 kPa, diameter is increased to 920 mm, height is increased by 300 mm.</p> <p>As technical air is not useable for arc extinction, another principle must be applied, e.g., a vacuum interrupter and a suitable drive.</p> <p>Assumptions: Material of basic drive structure can be reduced by 50%, material of energy storage can be reduced by 75%.</p>
Disconnecter and earthing switches, make proof earthing switches	<p>Mechanisms to increase disconnector opening speed must be foreseen due to limited thermal properties of gas.</p> <p>Assumption: Contact system is mechanically more complex but does not need more drive energy. Material increase is not significant.</p>	
Instrument transformers	<p>Wiring insulation must be in a different gas compartment as interrupter due to limited chemical resistance.</p>	No impact

Few design changes with low impact on inventory have been cut off in this study. Table 3 electrical resistance is depending on several parameters, which can be identified only after detailed design, conductivity and dimensioning of conductors, single flat contact of vacuum interrupter compared to multiple contacts of gas interrupter, etc. For sake of simplicity, power losses have been kept the same as for SF<sub>6</sub>.

- Circuit breaker interrupter unit is considered like SF<sub>6</sub> solution for both options regarding inventory.

### 2.2.6 Scenarios

Assumptions were variated within reasonable boundaries. The impact on life cycle inventory was estimated and if an impact of more the 3% on the environmental footprint could be expected, they were considered in scenarios. Those scenarios are listed in Table 4. Base scenarios with assumptions as described before for option 1 and option 2 are 1.0 and 2.0 respectively.

Table 4. Scenarios

No.	Name	Parameter changes
1.1/2.1	Aluminium 2050 (Circular Economy)	Recycled material content for Aluminium increased to 100%. These parameters are applied to both options.
2.2	Light circuit breaker	Circuit breaker pressure decreased to 700 kPa, diameter decreased to 880 mm for option 2.
2.3	Heavy circuit breaker	Circuit breaker pressure increased to 880 kPa, diameter increased to 1 000 mm for option 2.
2.4	Low dye cast effect	50% of the cast enclosure wall thickness increase can be avoided by changing process to dye cast for option 2.
1.2	Heavy leakage rate	Leakage rate for option 1 increased to 0.5%.

## 2.2.7 Allocation

### 2.2.7.1 End-of-Life Allocation

End-of-Life allocation follows the requirements of ISO 14044. Such allocation approaches address the question of how to assign impacts from virgin production processes to material that is recycled and used in future product systems. Two main approaches are commonly used in LCA studies to account for end-of-life recycling and recycled content. This study uses the latter – Cut-off approach.

- Substitution approach (also known as 0:100, closed-loop approximation, recyclability substitution or End-of-Life approach) – this approach is based on the perspective that material that is recycled into secondary material at End-of-Life will substitute for an equivalent amount of virgin material. Hence, a credit is given to account for this material substitution. However, this also means that burdens equivalent to this credit should be assigned to scrap used as an input to the production process, with the overall result that the impact of recycled granulate is the same as the impact of virgin material. This approach rewards End-of-Life recycling but does not reward the use of recycled content.
- Cut-off approach (also known as 100:0 or recycled content approach) – burdens or credits associated with material from previous or subsequent life cycles are not considered i.e., are “cut-off”. Therefore, scrap input to the production process is free of burdens but, equally, no credit is received for scrap available for recycling at End-of-Life. This approach rewards the use of recycled content but does not reward End-of-Life recycling.

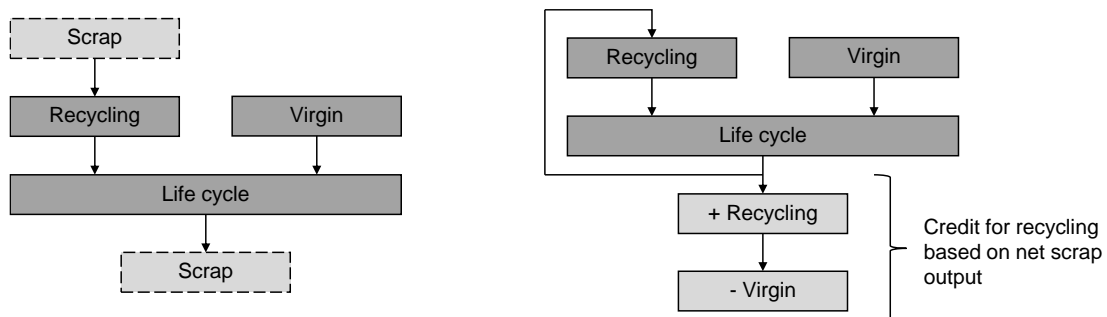


Figure 3. Schematic representations of the cut-off and substitution approaches.

Material recycling (substitution approach): Open scrap inputs from the production stage are subtracted from scrap to be recycled at End-of-Life to give the net scrap output from the product life cycle. This remaining net scrap is sent to material recycling. The original burden of the primary material input is allocated between the current and subsequent life cycle using the mass of recovered secondary material to scale the substituted primary material, i.e., applying a credit for the substitution of primary material to distribute burdens appropriately among the different product life cycles. These subsequent process steps are modelled using industry average inventories.

Energy recovery (substitution approach): In cases where materials are sent to waste incineration, they are linked to an inventory that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. Credits are assigned for power and heat outputs using the regional grid mix and thermal energy from natural gas. The latter represents the cleanest fossil fuel and therefore results in a conservative estimate of the avoided burden.

Landfilling (substitution approach): In cases where materials are sent to landfills, they are linked to an inventory that accounts for waste composition, regional leakage rates, landfill gas capture as well as utilization rates (flaring vs. power production). A credit is assigned for power output using the regional grid mix

### 2.2.8 Cut-off Criteria

No cut-off criteria are defined for this study. As summarized in 2.2.3, the system boundary was defined based on relevance to the goal of the study. For the processes within the system boundary, all available energy and material flow data have been included in the model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

### 2.2.9 Type and Format of the Report

In accordance with the ISO requirements (ISO 14044, 2006)<sup>7</sup> this document aims to report the results and conclusions of the LCA completely, accurately and without bias to the intended audience. The results, data, methods, assumptions and limitations are presented in a transparent manner and in sufficient detail to convey the complexities, limitations, and trade-offs inherent in the LCA to the reader. This allows the results to be interpreted and used in a manner consistent with the goals of the study.

### 2.2.10 Software and Database

The LCA model was created using the GaBi 9 Software system for life cycle engineering, developed by Sphera Solutions Inc. The GaBi 2021 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

### 2.2.11 Critical Review

Third party review according to ISO 14044, has been conducted together with the Hitachi Energy Power Consulting internal quality assessment process. The reviewer has been Håkan Strippel (Hakan.Strippel@IVL.se) at IVL Swedish Environmental Research Institute (www.IVL.se). Håkan Strippel is an external independent verifier in the International EPD system (Environmental Product Declaration), www.environdec.com. He has more than 30 years of experience from LCA and is a Chemical Engineer from Chalmers University of Technology, Sweden.

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### 3 Life cycle inventory analysis

This section provides a brief overview of the type of background data used in the comparison of the ELK-04, 145 kV designs and gives insight into the specific data that was used in the LCA model.

#### 3.1 Data collection procedure

Primary data were collected using customized data collection templates. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, stoichiometry, as well as internal and external benchmarking.

#### 3.2 Product System GIS ELK-04, 145 kV

##### 3.2.1 Overview of Product System

Main impact on material composition is on Aluminium and stemming from the insulation properties. For option 1, the  $(CF_3)_2CFCN$  mixture means that the basic dimensions like flange diameter and overall module size can remain basically the same except for the additionally exhaust volume of the circuit breaker, but design pressure must be increased. For option 2, technical air, this results in that both basic dimensions and pressure must be increased. Increase of wall thickness due to higher pressure can be limited to some extent by changing to a better cast quality in terms of inner material structure and surface roughness, using dye cast instead of sand cast.

Other effects are:

- Overall heavier design of option 2 results in a stronger steel structure.
- Bigger module dimensions of option 2 result in longer conductors, both Aluminium and copper.
- Bigger flange dimensions of option 2 result in a bigger insulators made for epoxy resin.
- Drive energy and related material need of option 1 are higher due to the usage of self-blast breaker technology instead of vacuum technology.

Table 5. Material composition (in kg) per functional unit.

Material	Option 0	Option 1	Option 2
Aluminium	1 577.7	1 950.7	2 676.7
Steel	750.8	774.4	851.4
Copper	407.9	407.9	488.3
Epoxy resin	181.2	219.9	407.2
Stainless steel	85.2	90.5	136.1
Thermoplastics	58.4	58.4	65.5
Rubber	05.6	6.0	11.2
Silver	00.7	0.7	1.0
Other materials	01.7	1.7	2.5
Gas	80.3	35.3	0.0
Packaging	130.0	130.0	130.0
Total	3 279.5	3 675.6	4 769.8

### 3.2.2 Component Transport

70% of Aluminium components are sourced out of Asia, 30% out of Europe. Other materials are mainly sourced out of Europe. For all component lorry transports, a distance of 1 500 km within Europe are assumed and 70% of used Aluminium are transported 10 000 km by ship in addition.

Table 6. Transportation and distance of components.

Transportation	Option 0	Option 1	Option 2
Lorry / tkm	4 919	5 513	7 155
Ship / tkm	11 044	13 655	18 737

### 3.2.3 Production

As Hitachi energy factories are producing several types of gas insulated switchgear, which have different primary ratings and different dimensions. The energy consumption per unit is calculated based on measured data from factory in Zurich, CH and scaled by the ratio of unit's weight and total weight of all units produced within one year.



Table 7. Energy and water use per functional unit.

Resource	Option 0	Option 1	Option 2
Electricity / kWh	125	140	182
District heat / kWh	258	289	376
Water / m <sup>3</sup>	0.3	0.4	0.5

Waste is calculated with 8% of the total GIS weight.

Gas losses during assembly and testing are estimated based on actual factory reporting and production volume with 0.14% of the gas content.

### 3.2.4 Transport to customers

After being produced, the product is sold to different customers in Europe. For this screening study, it was assumed that 40% of the products were transported 1 000 km by truck to reach the customer, and the remaining 60% of the products were transported in a combination including 450 km by truck, followed by 960 km by ship and 300 km by truck to reach their destination. The following assumptions of the types of transport modes were made: Euro 6 truck, 28-32 t gwt and ocean-going container ship, 5 000 to 200 000 dwt payload capacity.

### 3.2.5 Use Phase

Power losses

Although nominal current ratings are typically in the range of 3 150 A for 145 kV-GIS, the actual load is usually well below that. Therefore, it is assumed with 800 A according to typical current transformer ratings.

As products utilizing SF<sub>6</sub> alternatives are delivered to customers in countries with a relatively strong environmental focus, it is assumed that power is generated from renewable resources over most of the lifetime of GIS.

Table 8. Data for calculation of losses.

Parameter	Unit	Value
Current	A	800
Lifetime	a	40
Lifetime	h	350 400
Phases		3
Resistance per phase (μOhm)	μOhm	75
Primary losses $R \cdot I^2$	W	48
Secondary losses	W	130
Power losses, annual	MWh	4.7
Power losses, lifetime	MWh	187

The electricity losses were modelled assuming a grid mix featuring power supply exclusively from renewable resources (hydropower used as an example). Losses of the insulating gas in the use phase were considered for the complete lifetime of an ELK-04. Results are based on a lifetime of 40 years.

### Gas Leakages

Standardized gas leakage levels are 0.1% for type testing of equipment and 0.5% for routine testing of equipment. During use phase, gas leakages vary strongly and is depending on design and maintenance.

Product design has been improved in recent years by using O-Rings with extremely low permeability. Furthermore, design for outdoor application and for other corrosive environments has further reduced the risk of leakages due to flange corrosion. In production, improved sniffing methods for SF<sub>6</sub> can reduce the routine test level to 0.1%. Hence, for well designed, tested and maintained equipment, 0.1% losses per year due to leakage can be assumed for SF<sub>6</sub>. However, as gas mixture for contain a much smaller portion of traceable gas for leakage testing, 0.2% losses per year are assumed here. Tracing of air leakages is even more difficult, but as GWP is zero, it can be neglected for option 2.

### 3.2.6 End-of-Life

The End-of-Life phase covers recycling of metals, incineration with energy recovery of thermoplastics, thermosets and packaging materials, and recovery of insulating gas for option 1 (no recycling was considered). A recycling rate of 100% was assumed for this study. The remaining materials were landfilled.

An average transport distance and mode to the sites of recycling and disposal was assumed as 500 km by truck (Euro 6 truck, 28-32 t gwt).

Energy and auxiliary materials needed for re-melting metal scrap to secondary materials that substitute primary materials were included in the disposal phase.

During the dismantling phase of the product, total losses of 1% of the insulating gas were considered.

## 3.3 Background Data

Documentation for all GaBi datasets can be found online (<https://sphaera.com/life-cycle-assessment-lca-database>)<sup>12</sup>.

### 3.3.1 Fuel and Energy

National averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2021 databases. Table 9 shows the most relevant LCI datasets used in modelling the product systems. Electricity consumption was modelled using national grid mixes that account for imports from neighboring countries/regions.

Table 9. Key energy datasets used in inventory analysis.

Energy	Location	Dataset	Data provider	Reference year
Natural gas	DE	Thermal energy from natural gas	Sphaera	2021
Technical heat	DE	District heating mix	Sphaera	2021
Electricity	EU-28	Electricity grid mix	Sphaera	2021
Electricity	Hydropower	Electricity grid mix	Sphaera	2021

### 3.3.2 Key Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2021 database.

Table 10. Key material and process datasets used in inventory analysis.

Material	Location	Dataset	Data provider	Reference year
Aluminium cast	DE	Aluminium die-casting (AlSiCu) Primary	Sphera	2021
Aluminium sheet	EU-28	Aluminium sheet (EN15804 A1-A3) / Aluminium sheet deep drawing (adjustable)	Sphera	2021
Extruded Aluminium	EU-28	Aluminium extrusion profile	Sphera	2021
Cold rolled steel	DE	Steel cold rolled coil 1.5 mm	Sphera	2021
Steel sheet	DE	Steel sheet parts (steel hot rolled coil)	Sphera	2021
Cold rolled stainless steel	DE	Stainless steel cold roll	Sphera	2021
Copper wire	EU-28	Copper wire (0.06 mm)	Sphera	2021
Other copper/copper alloys	GLO	Copper mix (99.999% from electrolysis)	Sphera	2021
Epoxy with quartz sand filler	DE	Epoxy Resin (EP)	Sphera	2021
PVC	DE	Polyvinyl chloride granulate (E-PVC)	Sphera	2021
Hot galvanized steel	DE	Steel sheet parts (galvanized)	Sphera	2021
Wood pallets	DE	Wooden pallets (EURO, 40% moisture)	Sphera	2021

The chosen metal LCIs reflect typical shares of secondary material inputs, which have a relevant influence on the LCA results. For example, all Aluminium materials are produced from 100% virgin material.

### 3.3.3 Transportation

Average transportation distances and modes of transport are included for the transport of the raw materials and auxiliary materials to the assembly facility, transport of the finished product to customers, and transport of the used product to the dismantling/recycling facility.

The GaBi 2021 database was used to model transportation. Transportation was modelled using the GaBi global transportation datasets. Fuels were modelled using the geographically appropriate datasets.

Table 11. Transportation and road fuel datasets.

Mode/fuel	Location	Dataset	Data provider	Reference year
Euro 6 truck, 28-32t gwt	GLO	Truck, Euro 6, 28 - 32t gross weight / 22t payload capacity	Sphera	2021
Container ship, 5000-200000 dwt	GLO	Container ship, 5,000 to 200,000 dwt payload capacity, ocean going	Sphera	2021
Diesel	DE	Diesel mix at refinery	Sphera	2021
Heavy fuel oil	DE	Heavy fuel oil at refinery (1.0 wt.% S)	Sphera	2021

## 4 Life cycle impact assessment

This chapter contains the results for the impact categories and additional metrics defined in section 4.1.1. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach).

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

### 4.1 Environmental Impact Categories and Interpretation approach

#### 4.1.1 Selection of LCIA Methodology and Impact Categories

The impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 12.

Global warming potential was chosen because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest, and deemed to be the most pressing environmental issues of our time.

Eutrophication, acidification, and photochemical ozone creation potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burdens associated with commonly regulated emissions such as NO<sub>x</sub>, SO<sub>2</sub>, VOC, and others.

Ozone depletion potential was chosen because of its high political relevance, which eventually led to the worldwide ban of more active ozone-depleting substances; the phase-out of less active substances is due to be completed by 2030. Current exceptions to this ban include the application of ozone depleting chemicals in nuclear fuel production. The indicator is therefore included for reasons of completeness.

The present study also includes the assessment of abiotic resources to measure mineral and fossil resource inputs in life cycle impact assessment.

Table 12. Impact category descriptions

Impact Category	Description	Unit	Reference
<b>Climate change (global warming potential)</b>	A measure of greenhouse gas emissions, such as CO <sub>2</sub> and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO <sub>2</sub> equivalent	(IPCC, 2013) <sup>11</sup>
<b>Acidification Potential</b>	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H <sup>+</sup> ) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	moles H <sup>+</sup> equivalent	(Seppälä J., 2006 <sup>13</sup> ; Posch, 2008 <sup>12</sup> )
<b>Eutrophication (terrestrial, freshwater, marine)</b>	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	Terrestrial: moles N equivalent Freshwater: kg P equivalent Marine: kg N equivalent	(Seppälä J., 2006 <sup>13</sup> ; Posch, 2008 <sup>12</sup> )
<b>Ozone Depletion</b>	A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth's surface with detrimental effects on humans and plants.	kg CFC-11 equivalent	(Guinée, et al., 2002) <sup>5</sup>
<b>Photochemical Ozone Formation</b>	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O <sub>3</sub> ), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.	kg C <sub>2</sub> H <sub>4</sub> equivalent	(Van Zelm R., 441-453) <sup>16</sup>
<b>Resource use, minerals and metals (Abiotic depletion elements)</b>	The consumption of non-renewable resources leads to a decrease in the future availability of the functions supplied by these resources. Depletion of mineral resources and non-renewable energy resources are reported separately. Depletion of mineral resources is assessed based on ultimate reserves.	kg Sb equivalent, MJ (net calorific value)	(Guinée, et al., 2002) <sup>5</sup>

<b>Resource use, energy carriers (Abiotic depletion fossil)</b>	A measure of the total amount of non-renewable primary energy extracted from the earth. Resource use is expressed in energy demand from non-renewable resources including both fossil sources (e.g. petroleum, natural gas, etc.) and uranium for nuclear fuel. Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.	MJ	(Guinée, et al., 2002 <sup>5</sup> ; van Oers, de Koning, Guinée, & Huppes, 2002 <sup>15</sup> )
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It shall be noted that the above impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the functional unit (relative approach).

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

As this study intends to support comparative assertions to be disclosed to third parties, no grouping or further quantitative cross-category weighting has been applied. Instead, each impact is discussed in isolation, without reference to other impact categories, before final conclusions and recommendations are made.

#### 4.1.2 Interpretation approach

The interpretation approach addresses the following topics:

- Identification of significant findings, such as the main process step(s), material(s), and/or emission(s) contributing to the overall results
- Evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data.
- Conclusions and recommendations

Note that in situations where no product outperforms all of its alternatives in each of the impact categories, some form of cross-category evaluation is necessary to draw conclusions regarding the environmental superiority of one product over the other.

Since ISO 14044 rules out the use of quantitative weighting factors in comparative assertions to be disclosed to the public, this evaluation will take place qualitatively and the defensibility of the results therefore depend on the authors' expertise and ability to convey the underlying line of reasoning that led to the final conclusion.

## 4.2 ELK-04, 145kV GIS design options LCA - Results

The following section presents the results of the LCA study, providing insight to the life cycle environmental impact of the ELK-04 GIS. Climate change and carbon emissions (GWP) has been selected as a focal point, providing an overview of the life cycle environmental impact. In addition, GWP is strongly affected by emissions of insulation gases such as SF<sub>6</sub>, which is used to provide a comparison to the two options and the scenarios presented in this study.

The results are presented as per functional unit, which is the operation of the GIS for a 40-year lifetime. Complete data for all selected environmental impact categories are presented graphically and in table format.

### 4.2.1 Comparison between option 1 and option 2

For a 40-year operational lifetime and with power losses covered by electricity production coming exclusively from renewable resources, focus is placed on the impact of manufacturing and End-of-Life as well as gas leakage.

Though option 1 carries the additional impact of gas leakage over the product lifetime, this accounts for 2% of the total and does not outweigh the additional impact of manufacturing and End-of-Life for option 2. The total contribution to GWP is 20% lower for option 1 when compared to option 2 (see Figure 4).

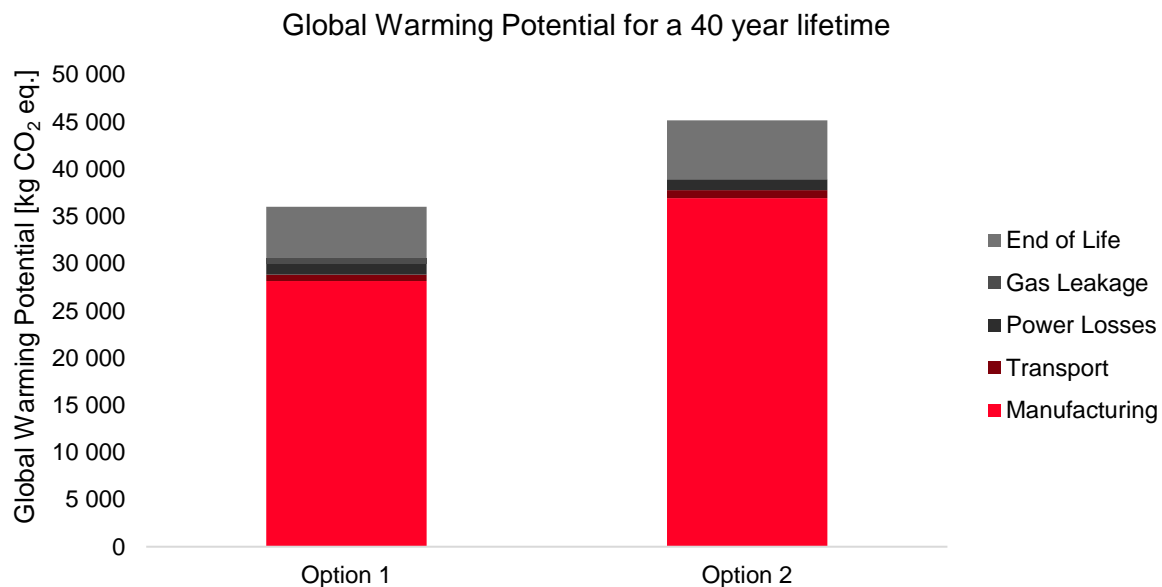


Figure 4. Comparison of the GWP between option 1 and option 2 for a 40-year lifetime. Power losses covered exclusively from renewable resources.

Comparing the above options with a solution utilizing SF<sub>6</sub> (ELK-04, 145 KV) as an insulating gas, alternative designs ELK-04-145E3 (C4FN) and ELK04-145A (Vacuum) have a lower (72% and 65% respectively) life cycle impact on GWP (see Figure 5).

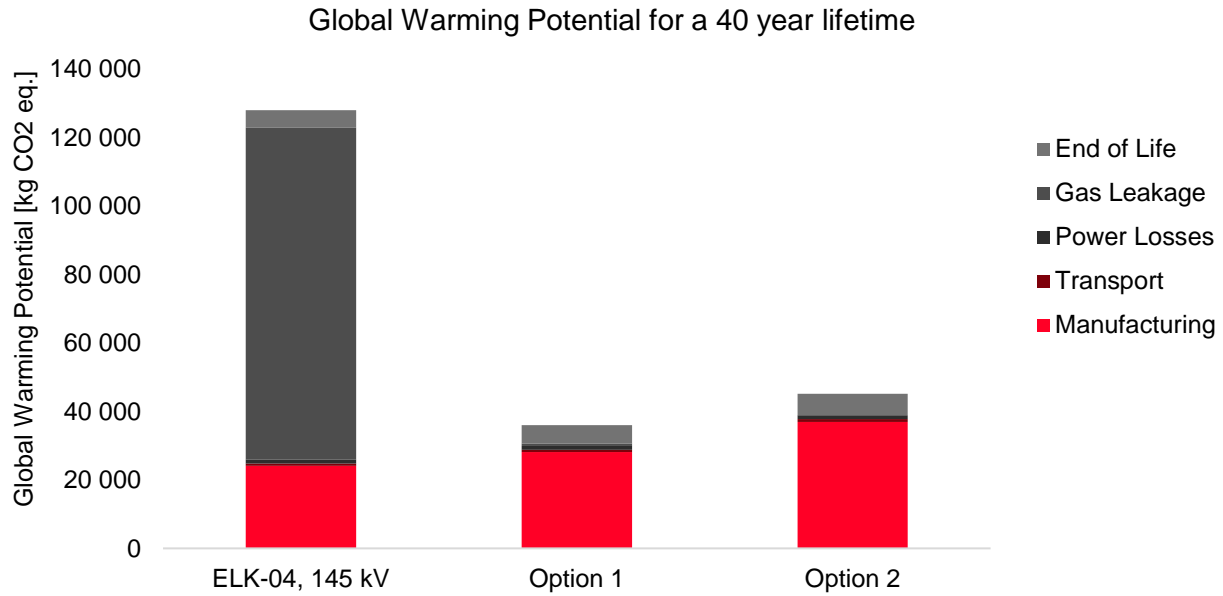


Figure 5. Comparison of the GWP between a solution utilizing SF<sub>6</sub> as insulating gas Vs option 1 and option 2 for a 40-year lifetime. Power losses covered exclusively from renewable resources.

### 4.3 Comparative scenario overview

In scenarios assuming recycled Aluminium content of 100% in manufacturing, the reduction when compared to the solution utilizing SF<sub>6</sub> is even greater for ELK-04-145E3 (C4FN) and ELK04-145A (Vacuum) at 84% and 82% respectively.

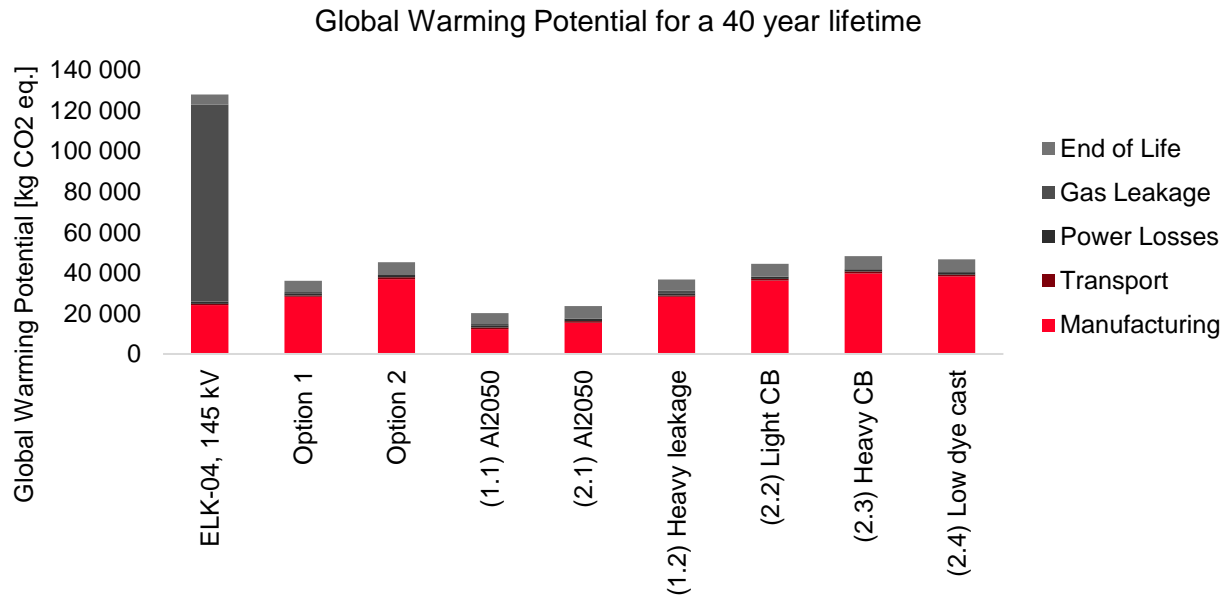


Figure 6. Comparative overview of the impact on GWP/FU for all scenarios over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.



Assuming a heavy leakage of 5% per year for ELK-04-145E3 (C4FN), the reduction of life cycle impact on GWP against ELK-04, 145 KV is 71%. Modelling option 2 with a lighter or a heavier circuit breaker as well as the low dye cast scenario provides for an impact that is 65%, 62% and 64% lower than the impact of the solution utilizing SF<sub>6</sub> (see Figure 5). Option 1 provides the greatest reduction in impact, overall with a 71% reduction to the SF<sub>6</sub> solution and an 84% reduction when assuming a recycled Aluminium content of 100% in the manufacturing process (see Table 13).

Table 13. Comparative reduction of impact on GWP for all designs when compared to a solution utilizing SF<sub>6</sub>, over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

GWP 100	Total (kg CO <sub>2</sub> eq./FU)	Reduction vs SF <sub>6</sub>
<b>ELK-04, 145 KV (SF<sub>6</sub>)</b>	127 953	
<b>Option 1</b>	36 022	71%
<b>Option 2</b>	45 180	65%
<b>(1.1) Al2050</b>	20 206	84%
<b>(2.1) Al2050</b>	23 662	81%
<b>(1.2) Heavy leakage</b>	36 780	70%
<b>(2.2) Light CB</b>	44 445	65%
<b>(2.3) Heavy CB</b>	48 186	62%
<b>(2.4) Low dye cast</b>	46 626	63%

Table 14. Impact on GWP for all designs by life cycle stage, over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

GWP 100 (kg CO <sub>2</sub> eq./FU)	Manufacturing	Transport	Power Losses	Gas Leakage	End-of-Life
<b>ELK-04, 145 KV (SF<sub>6</sub>)</b>	24 127	602	1 152	96 632	5 130
<b>Option 1</b>	28 142	670	1 152	1 251	5 427
<b>Option 2</b>	36 936	826	1 152	0	6 266
<b>(1.1) Al2050</b>	12 331	670	1 152	1251	5 422
<b>(2.1) Al2050</b>	15 413	827	1 152	0	6 271
<b>(1.2) Heavy leakage</b>	28 136	670	1 152	2893	5 422
<b>(2.2) Light CB</b>	36 235	817	1 152	0	6 242
<b>(2.3) Heavy CB</b>	39 780	867	1 152	0	6 387
<b>(2.4) Low dye cast</b>	38 302	846	1 152	0	6 326

When assessing option 1 and option 2 through the remaining environmental impact categories, the same trend is apparent with option 1 having the lowest impact for all categories. As SF<sub>6</sub> impacts GWP and not the other categories included in this study, a comparison to the design using SF<sub>6</sub> as an insulating gas shows that the total life cycle impact is lower than both options 1 and 2, as the manufacturing impact of the SF<sub>6</sub> design is lower overall.

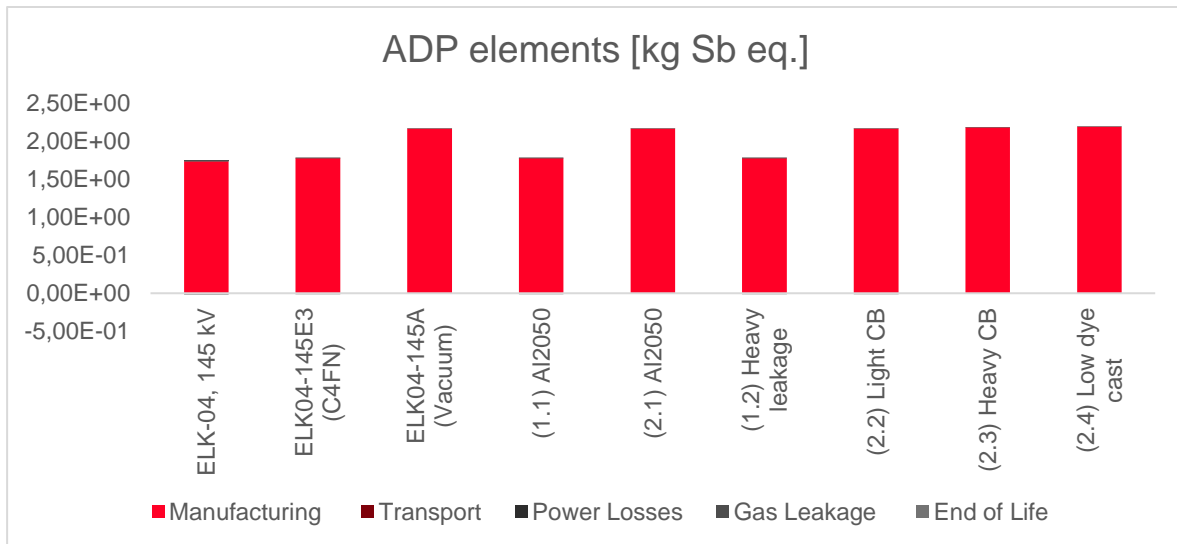


Figure 7. Comparative overview of the impact on ADP elements/FU for all scenarios over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

Table 15. Impact on ADP elements/FU for all designs by life cycle stage, over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

ADP elements [kg Sb eq./FU]	Manufacturing	Transport	Power Losses	Gas Leakage	End-of-Life	Total
ELK-04, 145 KV (SF <sub>6</sub> )	1.73E+00	5.74E-05	5.11E-03	4.14E-06	-1.64E-02	1.72E+00
Option 1	1.78E+00	6.39E-05	5.11E-03	5.39E-08	-1.46E-02	1.77E+00
Option 2	2.16E+00	7.88E-05	5.11E-03	0.00E+00	-1.12E-02	2.16E+00
(1.1) Al2050	1.78E+00	6.39E-05	5.11E-03	5.39E-08	-1.46E-02	1.77E+00
(2.1) Al2050	2.16E+00	7.88E-05	5.11E-03	0.00E+00	-1.12E-02	2.16E+00
(1.2) Heavy leakage	1.78E+00	6.39E-05	5.11E-03	1.35E-07	-1.46E-02	1.77E+00
(2.2) Light CB	2.16E+00	7.79E-05	5.11E-03	0.00E+00	-1.15E-02	2.16E+00
(2.3) Heavy CB	2.18E+00	8.26E-05	5.11E-03	0.00E+00	-9.86E-03	2.18E+00
(2.4) Low dye cast	2.19E+00	8.06E-05	5.11E-03	0.00E+00	-1.05E-02	2.18E+00

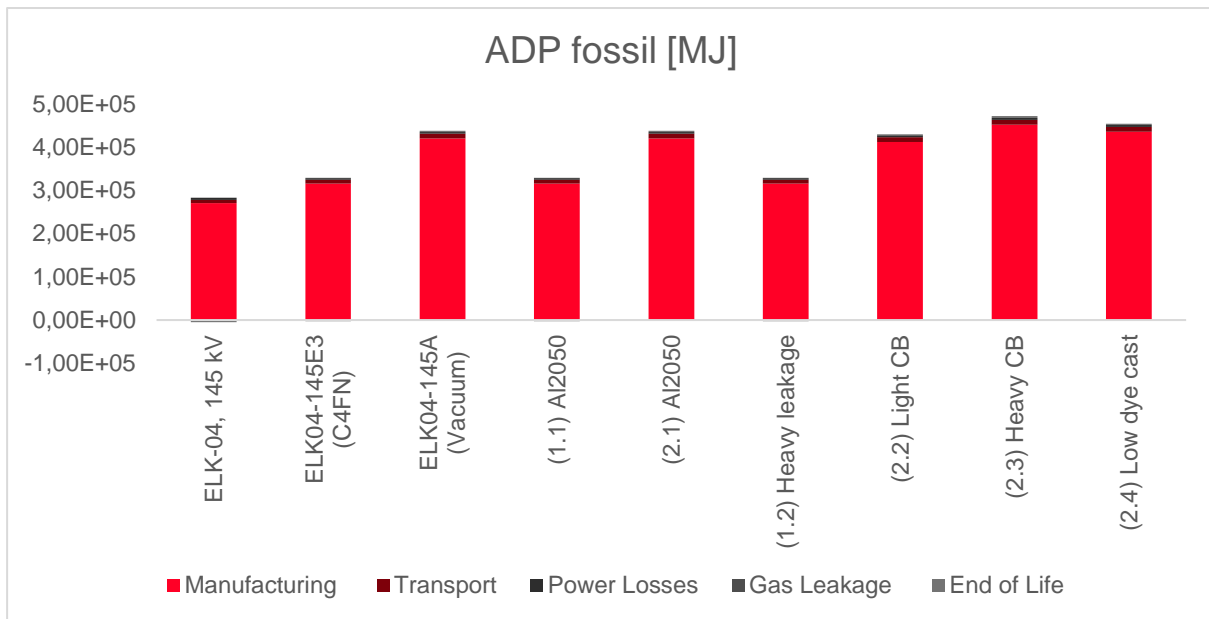


Figure 8. Comparative overview of the impact on ADP fossil/FU for all scenarios over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

Table 16. Impact on ADP fossil/FU for all designs by life cycle stage. over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

ADP Fossil [MJ/FU]	Manufacturing	Transport	Power Losses	Gas Leak-age	End-of-Life	Total
ELK-04, 145 KV (SF <sub>6</sub> )	2.71E+05	8.05E+03	4.11E+03	2.04E+02	-5.18E+03	2.78E+05
Option 1	3.16E+05	8.96E+03	4.11E+03	4.13E+00	-2.70E+03	3.26E+05
Option 2	4.21E+05	1.10E+04	4.11E+03	0.00E+00	2.66E+03	4.38E+05
(1.1) Al2050	3.16E+05	8.95E+03	4.11E+03	4.13E+00	-2.71E+03	3.26E+05
(2.1) Al2050	4.21E+05	1.10E+04	4.11E+03	0.00E+00	2.66E+03	4.39E+05
(1.2) Heavy leakage	3.16E+05	8.95E+03	4.11E+03	1.03E+01	-2.71E+03	3.26E+05
(2.2) Light CB	4.13E+05	1.09E+04	4.11E+03	0.00E+00	2.23E+03	4.30E+05
(2.3) Heavy CB	4.53E+05	1.16E+04	4.11E+03	0.00E+00	4.37E+03	4.73E+05
(2.4) Low dye cast	4.36E+05	1.13E+04	4.11E+03	0.00E+00	3.47E+03	4.55E+05

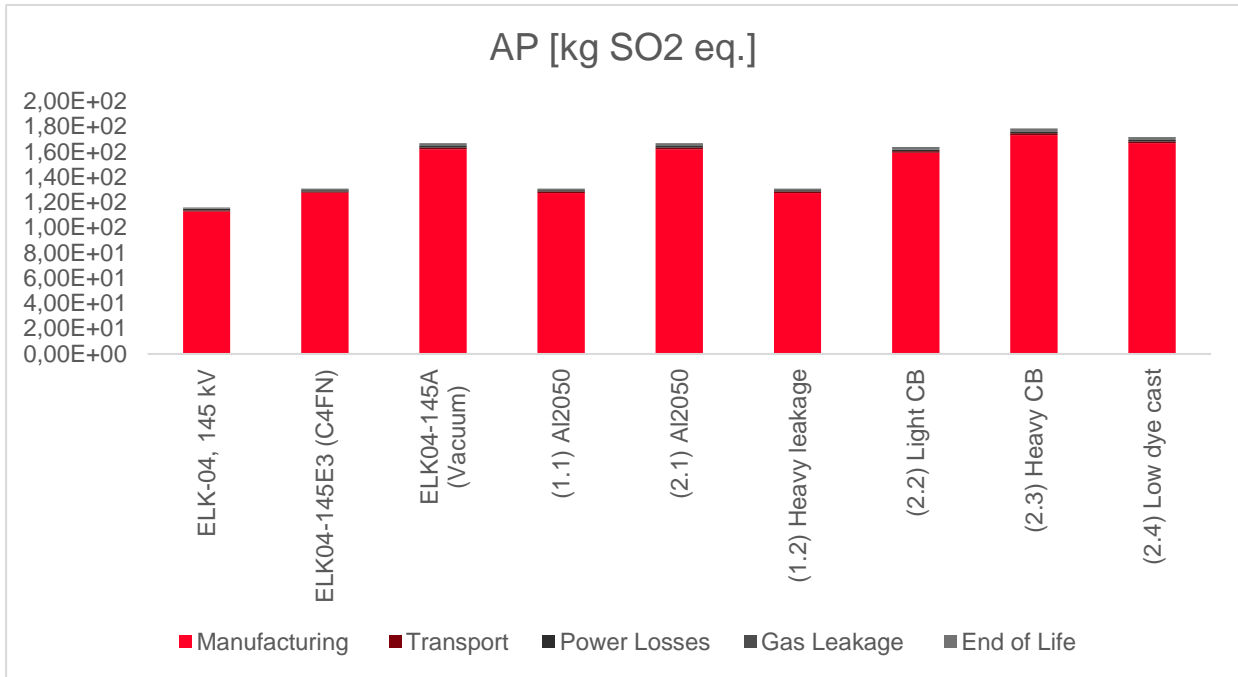


Figure 9. Comparative overview of the impact on AP/FU for all scenarios over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

Table 17. Impact on AP/FU for all designs by life cycle stage. over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

AP [kg SO <sub>2</sub> eq./FU]	Manufacturing	Transport	Power Losses	Gas Leak- age	End-of-Life	Total
ELK-04, 145 KV (SF <sub>6</sub> )	1.13E+02	9.81E-01	1.15E+00	3.92E-01	7.16E-01	1.16E+02
Option 1	1.27E+02	1.09E+00	1.15E+00	2.08E-04	1.19E+00	1.31E+02
Option 2	1.62E+02	1.35E+00	1.15E+00	0.00E+00	2.25E+00	1.67E+02
(1.1) Al2050	1.27E+02	1.09E+00	1.15E+00	2.08E-04	1.19E+00	1.31E+02
(2.1) Al2050	1.62E+02	1.35E+00	1.15E+00	0.00E+00	2.25E+00	1.67E+02
(1.2) Heavy leakage	1.27E+02	1.09E+00	1.15E+00	5.21E-04	1.19E+00	1.31E+02
(2.2) Light CB	1.59E+02	1.33E+00	1.15E+00	0.00E+00	2.18E+00	1.64E+02
(2.3) Heavy CB	1.73E+02	1.41E+00	1.15E+00	0.00E+00	2.56E+00	1.78E+02
(2.4) Low dye cast	1.67E+02	1.38E+00	1.15E+00	0.00E+00	2.40E+00	1.72E+02

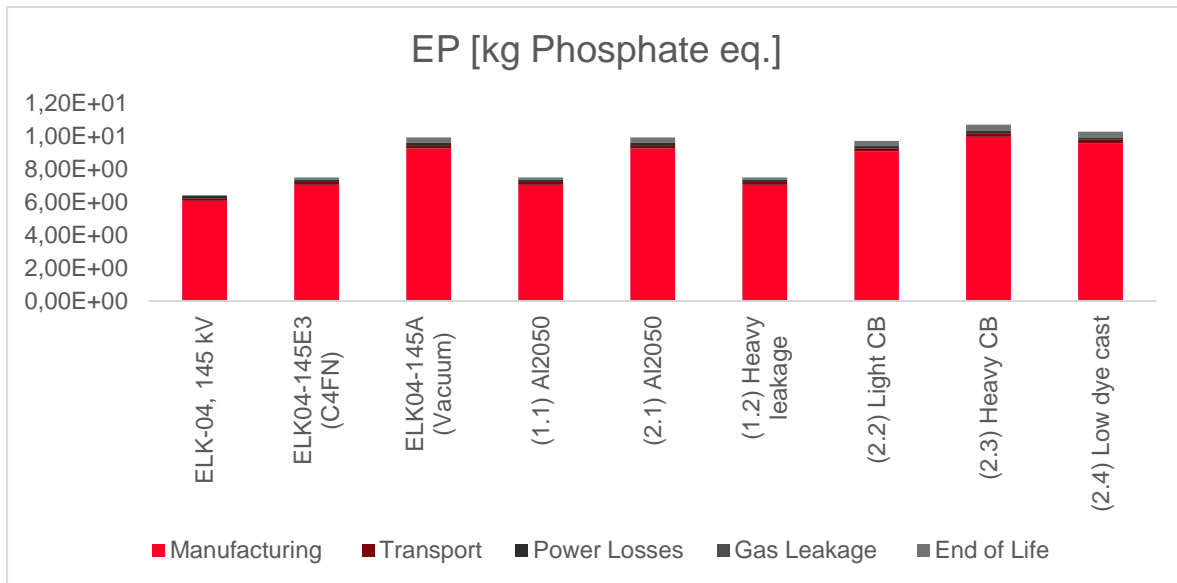


Figure 10. Comparative overview of the impact on EP/FU for all scenarios over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

Table 18. Impact on EP/FU for all designs by life cycle stage, over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

EP [kg Phos- phate eq./FU]	Manufacturing	Transport	Power Losses	Gas Leak- age	End-of- Life	Total
ELK-04, 145 KV (SF <sub>6</sub> )	6.09E+00	1.50E-01	1.35E-01	1.29E-02	5.02E-02	6.44E+00
Option 1	7.06E+00	1.66E-01	1.35E-01	3.80E-05	1.42E-01	7.50E+00
Option 2	9.25E+00	2.05E-01	1.35E-01	0.00E+00	3.32E-01	9.92E+00
(1.1) Al2O50	7.05E+00	1.66E-01	1.35E-01	3.80E-05	1.42E-01	7.50E+00
(2.1) Al2O50	9.25E+00	2.05E-01	1.35E-01	0.00E+00	3.32E-01	9.92E+00
(1.2) Heavy leakage	7.05E+00	1.66E-01	1.35E-01	9.50E-05	1.42E-01	7.50E+00
(2.2) Light CB	9.07E+00	2.02E-01	1.35E-01	0.00E+00	3.16E-01	9.72E+00
(2.3) Heavy CB	9.96E+00	2.15E-01	1.35E-01	0.00E+00	3.95E-01	1.07E+01
(2.4) Low dye cast	9.57E+00	2.10E-01	1.35E-01	0.00E+00	3.62E-01	1.03E+01

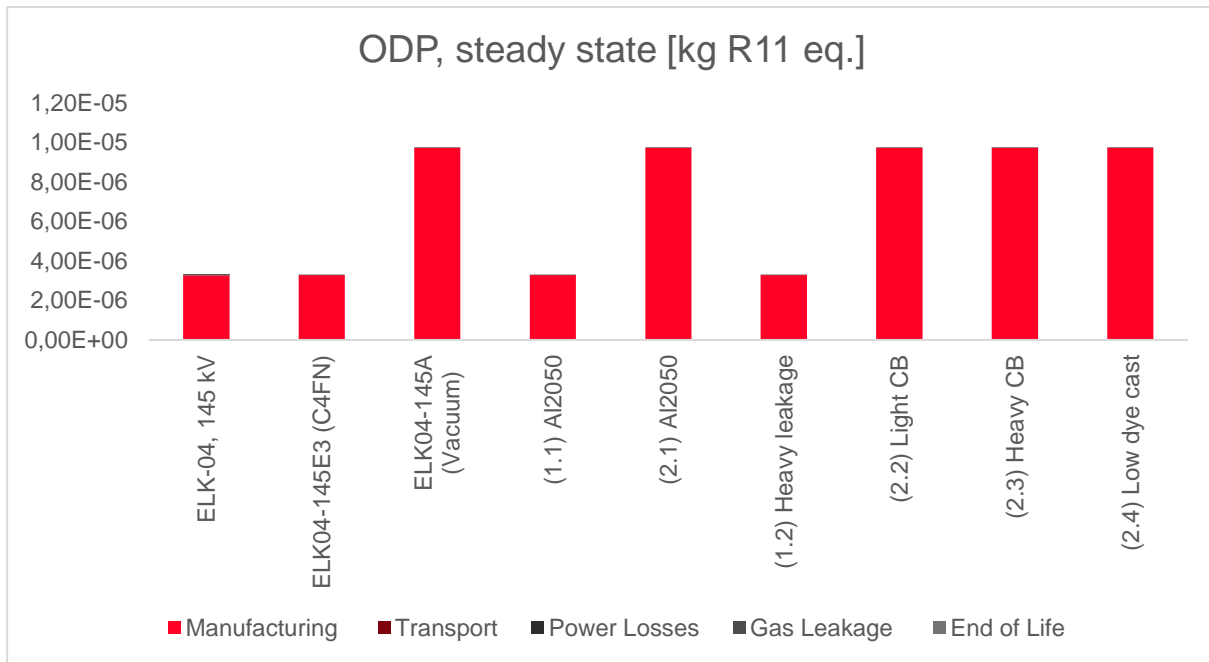


Figure 11. Comparative overview of the impact on ODP/FU for all scenarios over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

Table 19. Impact on ODP/FU for all designs by life cycle stage. over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

ODP, steady state [kg R11 eq./FU]	Manufacturing	Transport	Power Losses	Gas Leakage	End-of-Life	Total
<b>ELK-04, 145 KV (SF<sub>6</sub>)</b>	3.28E-06	2.07E-13	6.83E-10	3.85E-11	4.07E-11	3.28E-06
<b>Option 1</b>	3.29E-06	2.84E-13	6.83E-10	1.97E-15	4.50E-11	3.29E-06
<b>Option 2</b>	9.75E-06	2.30E-13	6.83E-10	0.00E+00	4.19E-11	9.75E-06
<b>(1.1) Al2050</b>	3.28E-06	2.30E-13	6.83E-10	1.97E-15	4.19E-11	3.28E-06
<b>(2.1) Al2050</b>	9.75E-06	2.84E-13	6.83E-10	0.00E+00	4.50E-11	9.75E-06
<b>(1.2) Heavy leakage</b>	3.28E-06	2.30E-13	6.83E-10	4.92E-15	4.19E-11	3.28E-06
<b>(2.2) Light CB</b>	9.75E-06	2.81E-13	6.83E-10	0.00E+00	4.49E-11	9.75E-06
<b>(2.3) Heavy CB</b>	9.75E-06	2.98E-13	6.83E-10	0.00E+00	4.55E-11	9.75E-06
<b>(2.4) Low dye cast</b>	9.75E-06	2.91E-13	6.83E-10	0.00E+00	4.52E-11	9.75E-06

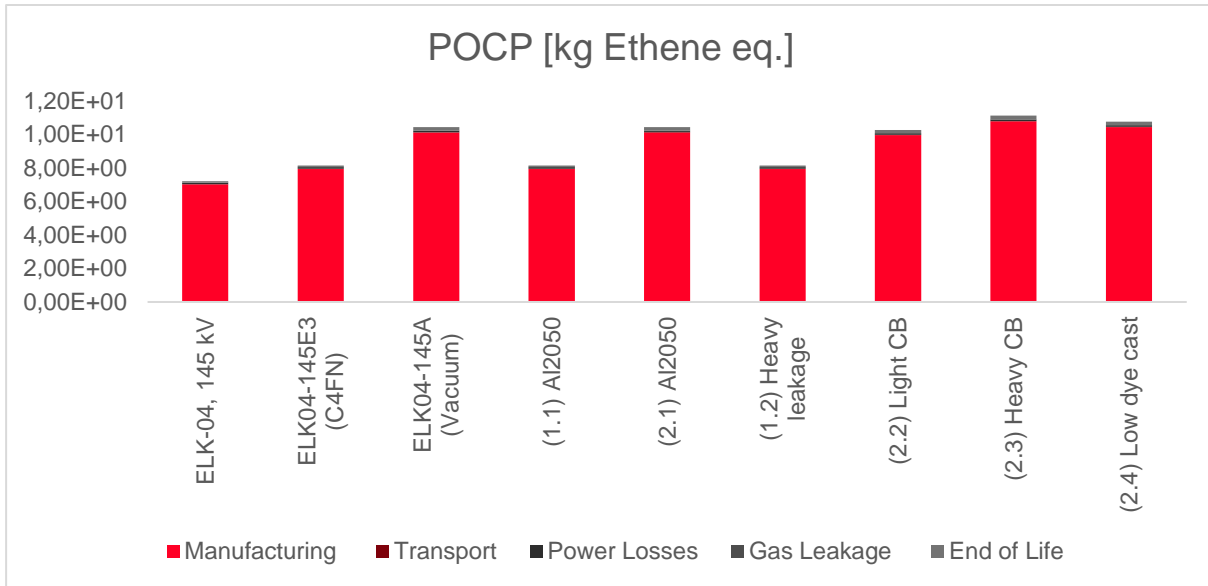


Figure 12. Comparative overview of the impact on POCP/FU for all scenarios over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

Table 20. Impact on POCP/FU for all designs by life cycle stage, over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively.

POCP [kg Ethene eq./FU]	Manufacturing	Transport	Power Losses	Gas Leakage	End-of-Life	Total
ELK-04, 145 KV (SF6)	7.02E+00	2.06E-02	8.56E-02	1.88E-02	6.28E-02	7.21E+00
Option 1	7.95E+00	2.29E-02	8.56E-02	4.44E-05	1.08E-01	8.17E+00
Option 2	1.01E+01	2.82E-02	8.56E-02	0.00E+00	2.13E-01	1.05E+01
(1.1) Al2050	7.95E+00	2.29E-02	8.56E-02	4.44E-05	1.07E-01	8.16E+00
(2.1) Al2050	1.01E+01	2.82E-02	8.56E-02	0.00E+00	2.13E-01	1.05E+01
(1.2) Heavy leakage	7.95E+00	2.29E-02	8.56E-02	1.11E-04	1.07E-01	8.16E+00
(2.2) Light CB	9.97E+00	2.79E-02	8.56E-02	0.00E+00	2.06E-01	1.03E+01
(2.3) Heavy CB	1.08E+01	2.96E-02	8.56E-02	0.00E+00	2.40E-01	1.11E+01
(2.4) Low dye cast	1.04E+01	2.89E-02	8.56E-02	0.00E+00	2.26E-01	1.08E+01

#### 4.4 Modelling Aluminium with the EC PEF Circular Footprint Formula

For informative purposes, the recycled content and recycling process of Aluminium was modelled according to the European Commission Circular Footprint Formula<sup>1,2,3</sup>. Aluminium is the most important raw material in this inventory. Therefore, main parameters of circular economy and the reasoning behind are described here using the settings of this material. As Aluminium is mainly used in long living goods like for instance buildings and planes, the actual amount of Aluminium in use is growing while a comparably small amount is released from usage. Therefore, low supply of recyclable materials and high demand can be assumed and burdens and credits between supplier and user of recycled materials are focused on supplier with an allocation factor of  $A = 0.2$ . Most of the Aluminium in GIS is used for pressurized enclosures and conductors. Besides mechanical strength, a good electrical conductivity and high corrosion resistance are required. As quality of alloys is most demanding and supply of recycle material is low, these components are made of primary Aluminium. Hence, the proportion of Aluminium in the input to the production that has been recycled from a previous system can be set to  $R_1 = 0$ .

On the other hand, at the End-of-Life, large (typically  $> 1$  kg) number of components, of high quality and easy to sort correctly, are available. Although they are out of control of GIS manufacturers, as end-of-life phase is managed by metal recycler rather than consumers and thus, the probability that this material is wasted is rather low. Hence, the proportion of Aluminium in the product that will be recycled (or reused) in a subsequent system is set to  $R_2 = 0.95$ . Majority of the Aluminium is AlSi7Mg0.3 and used for casting and contains – amongst other alloys – a rather high share of Si, which has to be removed prior to next usage. Quality of outgoing secondary material  $Q_{Sout}$  is measured by its content of pure Aluminium, which can be reused in subsequent products. On the other hand, quality of virgin material  $Q_P$  is set to one as this alloy is needed for casting. Therefore, the ratio of quality of the outgoing secondary material and quality of virgin material is resulting in  $Q_{Sout} / Q_P = 0.92$ . 8% of the virgin material are alloying addition. The formula below was applied to the modelling of Aluminium production and End-of-Life impact.

$$\begin{aligned}
 & \text{Life Cycle Inventory (LCI) of primary material} & \text{LCI associated to secondary material input} & \text{LCI of the material recycling (or part/product reuse) process minus the credit for avoided primary material} \\
 & \text{Material} & & \\
 & = (1 - R_1)E_V + R_1 \times \left( AE_{recycled} + (1 - A)E_V \times \frac{Q_{Sin}}{Q_P} \right) + (1 - A)R_2 \times \left( E_{recyclingEoL} - E_V^* \times \frac{Q_{Sout}}{Q_P} \right) \\
 & \text{Energy} & & \\
 & + (1 - B)R_3 \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec}) & & \\
 & \text{Disposal} & & \\
 & + (1 - R_2 - R_3) \times E_D & & \\
 & \text{LCI of the disposal of remaining waste} & \text{LCI of the energy recovery process minus the credit for avoided primary energy}
 \end{aligned}$$

Figure 13. The EC PEF Circular Economy Formula.

With the EC PEF Circular footprint formula used to model Aluminium production and End-of-Life, the credit from recycling processes allows for an overall reduction of the total life cycle impact. Option 1 provides a reduction of 80% when compared to the SF<sub>6</sub> design, while option 2 provides a reduction of 76%.



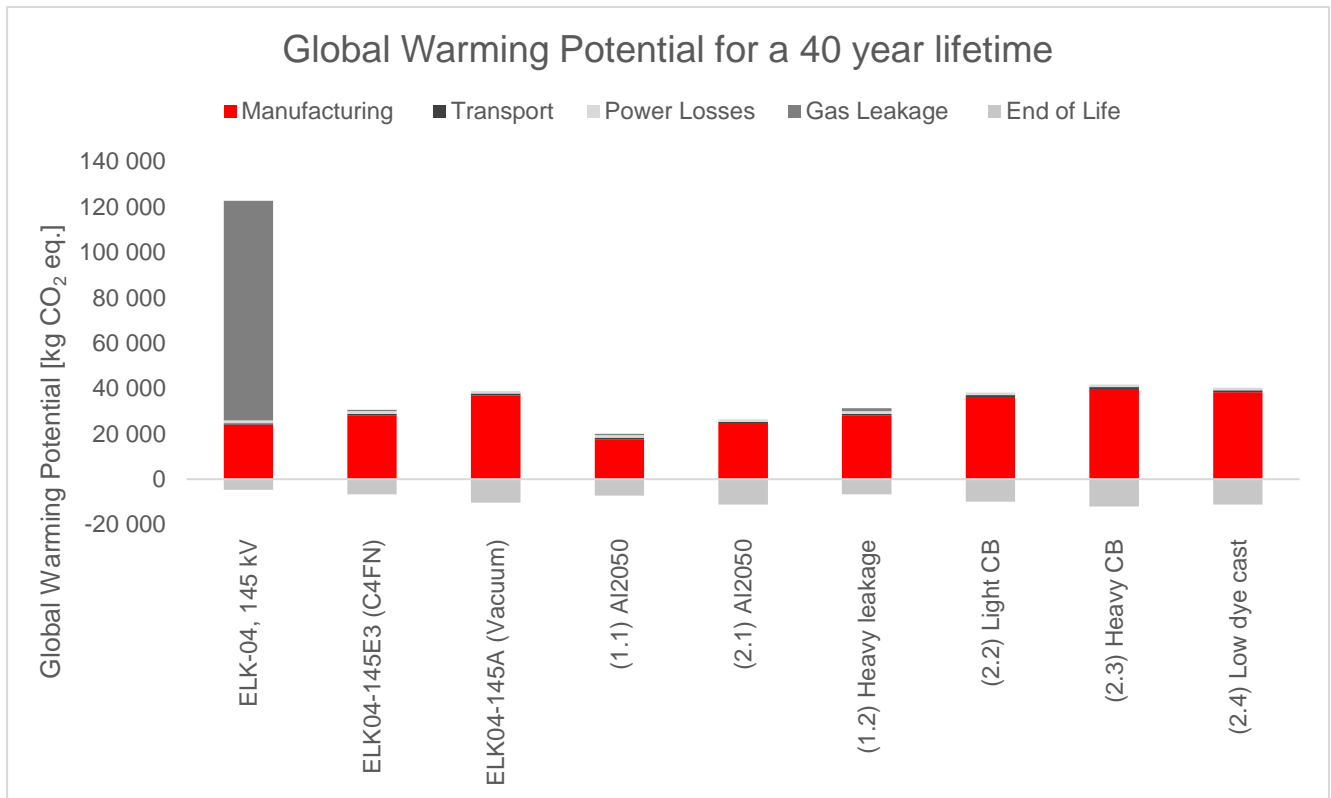


Figure 14. Comparative overview of the impact on GWP/FU for all scenarios over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively. Using the EC PEF Circular Footprint Formula to model Aluminium production and End-of-Life.

Increasing the recycled Aluminium content to 100% provides a reduction of 89% when comparing option 1 to the SF<sub>6</sub> design. while option 2 provides a reduction of 87% under the same conditions.

Table 21. Comparative overview of the impact on GWP/FU for all scenarios over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively. Using the EC PEF Circular Footprint Formula to model Aluminium production and End-of-Life.

	R1	R2	Total (kg CO <sub>2</sub> eq./FU)	% Reduction vs SF <sub>6</sub>
<b>ELK-04, 145 KV (SF<sub>6</sub>)</b>	0%	95%	118 133	
<b>Option 1</b>	0%	95%	23 888	80%
<b>Option 2</b>	0%	95%	28 516	76%
<b>(1.1) Al2050</b>	100%	100%	12 736	89%
<b>(2.1) Al2050</b>	100%	100%	15 130	87%
<b>(1.2) Heavy leakage</b>	0%	95%	24 646	79%
<b>(2.2) Light CB</b>	0%	95%	28 210	76%
<b>(2.3) Heavy CB</b>	0%	95%	29 789	75%
<b>(2.4) Low dye cast</b>	0%	95%	29 122	75%

Table 22. Impact on GWP/FU for all designs by life cycle stage, over a 40-year lifetime and power losses being covered with an electricity grid mix featuring renewable resources exclusively. Using the EC PEF Circular Footprint Formula to model Aluminium production and End-of-Life.

	Manufacturing	Transport	Power Losses	Gas Leakage	End of Life
<b>ELK-04, 145 KV (SF6)</b>	24 127	602	1 152	96 942	-4 690
<b>Option 1</b>	28 142	670	1 152	631	-6 707
<b>Option 2</b>	36 936	826	1 152	0	-10 398
<b>(1.1) Al2050</b>	17 589	670	1 152	631	-7 306
<b>(2.1) Al2050</b>	24 361	827	1 152	0	-11 209
<b>(1.2) Heavy leakage</b>	28 136	670	1 152	1 401	-6 712
<b>(2.2) Light CB</b>	36 235	817	1 152	0	-9 994
<b>(2.3) Heavy CB</b>	39 780	867	1 152	0	-12 010
<b>(2.4) Low dye cast</b>	38 302	846	1 152	0	-11 178

## 5 Life cycle interpretation

### 5.1 Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistent background LCA information from the GaBi 2021 database were used. The LCI datasets from the GaBi 2021 database are widely distributed and used with the GaBi 9 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets, they are crosschecked with other databases and values from industry and science.

#### 5.1.1 Precision and Completeness

- **Precision:** As the majority of the relevant foreground data are measured data or calculated based on primary information sources of the owner of the technology, precision is considered to be high. Seasonal variations/variations across different manufacturers were balanced out by using yearly averages/weighted averages. All background data are sourced from GaBi databases with the documented precision. Margins of error due to background data are managed through ensuring that all scenarios use the same datasets and follow the same assumptions for manufacturing processes, operation and End-of-Life.
- **Completeness:** Each foreground process was checked for mass balance and completeness of the emission inventory. No data were knowingly omitted. Completeness of foreground unit process data is considered to be high. All background data are sourced from GaBi databases with the documented completeness.

#### 5.1.2 Consistency and Reproducibility

- **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail, while all background data were sourced from the GaBi databases.
- **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input output data, dataset choices, and modelling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modelling approaches.

#### 5.1.3 Representativeness

- **Temporal:** All primary data were collected for the year 2020. All secondary data come from the GaBi 2021 databases and are representative of the years 2016-2020. As the study intended to compare the product systems for the reference year 2021, temporal representativeness is considered to be high.
- **Geographical:** All primary and secondary data were collected specific to the countries or regions under study. Where country-specific or region-specific data were unavailable, proxy data were used. Geographical representativeness is considered to be high.
- **Technological:** All primary and secondary data were modelled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used. Technological representativeness is high.

### 5.2 Model Completeness and Consistency

#### 5.2.1 Completeness

All relevant process steps for each product system were considered and modelled to represent each specific situation. The process chain is considered sufficiently complete and detailed with regards to the goal and scope of this study.

STATUS	SECURITY LEVEL	DOCUMENT ID	REV.	LANG.	PAGE
Approved	Public	202206_2665472	A	en	35/38

### 5.2.2 Consistency

All assumptions, methods and data are consistent with each other and with the study's goal and scope. Differences in background data quality were minimized by exclusively/predominantly using LCI data from the GaBi 2021 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

## 5.3 Conclusions, Limitations, and Recommendations

### 5.3.1 Conclusions

- Replacement of SF<sub>6</sub> by alternative insulation gases and arc extinguishing technologies leads to a reduction of global warming potential of 62% to 72%.
- Once SF<sub>6</sub> is replaced by an insulation medium that is two orders of magnitude lower in GWP, the effect of gas losses due to handling or leakage becomes circumstantial for both alternatives, C4-FN and technical air. The dominant impact is stemming from material usage, namely Aluminium.
- Due to the more compact design and smaller usage of materials, the overall life cycle impact of products is smaller for C4-FN than for technical air. This is the case for all investigated environmental impact categories.
- The conclusions above are valid for a broad range of assumptions (all scenarios), wherever estimates had to be used instead of measured data.
- The conclusions above are valid also when life cycle impact is modelled assuming a fully circular economy. This results from both, ISO compliant calculation and PEF compliant calculation.

### 5.3.2 Recommendations

Today's best available technology allows to basically eliminate the climate change impact of insulation and arc extinction media in gas insulated switchgear (reduction of more than 98%). This holds true even if one component of the medium still has a significant global warming potential by itself. A complete elimination of the climate change impact of the medium (reduction by 100%) comes at the expense of increased material use. This use will in turn lead to an increase of global warming and other undesirable environmental impacts of the whole equipment over its life cycle. This increase will overcompensate for the marginal reduction achieved by the medium. Therefore, it is recommended

- to ban SF<sub>6</sub>, in pure or in mixture, from use in gas insulated switchgear up to 145 kV wherever alternative insulation and arc extinction media are available.
- not to ban any gas other than SF<sub>6</sub> from use in gas insulated switchgear.

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## 7 Revisions

Rev.	Page (P) Chapt. (C)	Description	Date Dept./Init.