Evaluating SF_6-Free Solutions for Electric Switchgear in Offshore Electric Converter Stations: A Comparative Study

A case study of TenneT

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Executive summary

In the goal to become climate neutral, the Netherlands aims to phase out fossil fuels and expand the use of renewable energy, with a crucial role for offshore wind energy. The European Commission presented a strategy to increase the offshore renewable energy capacity by 30 times to 300 gigawatts in 2050, compared to 2020 levels. The wind farms currently being installed are connected to the European electricity grid via alternating current (AC) cables. As new farms are built further offshore, AC cables face significant losses exceeding 100 kilometres, making a transition to direct current (DC) the more efficient option. The 2-gigawatt program by TenneT focuses on connecting offshore wind farms with the onshore electricity grid through high voltage DC. Each offshore platform, standardized for deployment across Europe, connects 2 gigawatts from 100 to 150 wind turbines.

To be able to perform maintenance and secure safety, electrical switchgear is installed on the platform to connect and disconnect the wind turbines to the electricity grid. SF_6, utilized within this switchgear, poses significant environmental risks due to its high global warming potential (GWP) of 24300 compared to CO_2 and a atmospheric lifetime of 1278 years. Despite its technological superiority, the contribution to SF_6 emissions in the EU is concerning, especially with the projected increase in offshore capacity. In response, Regulation (EU) 2024/573 of the European Commission mandates a shift towards switchgear technologies with lower GWPs, requiring a GWP below 1 for switchgear up to 145kV from January 2028, with a two-year phase-out period for alternatives with a GWP below 1000 to avoid monopolies.

A transition towards SF_6 alternatives significantly impacts future developments in offshore wind energy, with required adaptations to offshore converter stations. As there is no consensus reached regarding the optimal alternative among academic literature and stakeholders, the research question of this study is: *What is the most viable alternatives to SF_6 in high-voltage switchgear for offshore converter stations, and how can its implementation be aligned with future platform developments and regulatory frameworks?* Using multi-criteria evaluation, 42 potential alternatives are evaluated with a GWP between 1 and 1000 and alternatives below a GWP of 1 based on the criteria GWP, ozone depletion potential, flammability, toxicity, boiling point and dielectric strength. As a result of the research, two viable alternatives were identified: a gas mixture of C_4F_7N, CO_2, and O_2 with a GWP between 301 and 614. This type can be installed until 2028 for switchgear rated up to 145kV, and potentially until 2030 if no other suppliers emerge. The second alternative is a vacuum GIS with a GWP of 0 which is insulated with clean air and interruption takes place under vacuum.

To assess the feasibility of vacuum GIS for future generation converter stations, drivers and challenges were explored through expert interviews. The primary challenges for vacuum GIS include its limited capacity of up to 145kV, the larger space requirements of the installation, and the limited number of manufacturers, with Siemens Energy currently being the sole high-voltage vacuum switchgear producer. A key driver is upgrading the inter-array cables between the turbines and the platform from 66kV to 132kV, allowing more turbines to connect per cable and reducing the number of switchgear installations from 40 to 24, which helps in saving space and costs. The capacity and space requirement challenges for future generation converter stations can be overcome with a transition to 132kV cables, for which the capacity of 145kV is sufficient, and the total space required for 24 vacuum switchgear installations is similar to 40 C_4F_7N or SF_6 installations which are installed in the first generation converter stations. The inter-array cables are unlikely to exceed capacities levels of 132kV, for which the limiting capacity of vacuum switchgear is not a barrier. Moreover, Hyundai Electric announced the development of a 145kV vacuum switchgear, which reduces the dependence on Siemens Energy.

While vacuum switchgear shows high potential for future implementation, Hitachi Energy and General Electric, two manufacturers of the C_4F_7N technology, have announced that they will continue operation and developments for this technology, motivated by the fact that the technology is more sustainable over the product lifecycle compared to the vacuum switchgear. This study evaluates this claim using life-cycle analysis (LCA) principles. Due to time constraints and limited available literature, this study focusses on the manufacturing and use phase of the LCA, as these contribute the most to greenhouse gas emissions and exhibit the most significant differences among SF_6, C_4F_7N, and vacuum technology. As a result, the C_4F_7N technology turns out to have the lowest total emissions over these two phases. Gas leakages from C_4F_7N installations result in significantly lower emissions compared to SF_6 installations. Additionally, the manufacturing of vacuum switchgear generates significantly more emissions than C_4F_7N switchgear due to the higher aluminum content of vacuum switchgear. While sustainable aluminum production could mitigate these emissions, there are currently no regulatory or economic incentives in place.

To answer the research question, vacuum switchgear turns out to be the most viable alternative to SF6 in high voltage switchgear for offshore converter stations, as this technology aligns with future platform developments and poses more regulatory compliance compared to the C_4F_7N installations. TenneT is advised to prepare for a transition to vacuum switchgear, supported by an upgrade to 132kV inter-array cables, which would facilitate a reduction in the number of switchgear installations from 40 to 24. This strategy not only aligns with regulatory mandates but also enhances the sustainability of offshore converter stations.

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1. Introduction

The Netherlands expanded the electricity grid over the last years to phase out the use of fossil fuels and intensify the use of electricity. The Netherlands aims to reduce greenhouse gas emissions by 55% in 2030 and reach net-zero in 2050 (Min. EZK, 2023). The European Commission has indicated that it considers a target of 26% renewables in the Dutch energy system to be reasonable for 2030 (Ministry of Economic Affairs and Climate Policy, 2019). The Netherlands Environmental Assessment Agency (PBL) estimates that the share of renewable energy in 2030 will be between 30 and 32% (Ministry of Economic Affairs and Climate Policy, 2019).

To achieve the target as set by the European Commission, the Netherlands presented plans to increase the share of offshore wind energy. The Dutch government has pointed out three additional locations for windfarms in the North Sea, through which the capacity will reach 21 gigawatts in 2030 (Min EZK., 2023). With a capacity of 21 gigawatt, 75% of the current Dutch electricity demand could be supplied by wind energy (Brandenburg et al., 2023). Offshore windfarm construction was initially subsidized under the Environmental Quality of Electricity Production and Sustainable Energy Production regulations. However, as economies of scale made the projects profitable, subsidies were repealed in 2018. While the farms are now financially self-sufficient, TenneT, the Dutch Transmission System Operator, covers the cost of connecting them to the national grid. With farms being built farther offshore, TenneT will have to find different grid connection systems compared to the currently existing ones.

The European electricity system is organized through Alternating Current (AC) because it is easier to increase and decrease voltage levels compared to Direct Current (DC). Wind turbines provide AC electricity and are therefore compliant to the electricity grid, without the need of converters. The already constructed windfarms in the North Sea are connected to land with AC cables. However, as future windfarms are built further off the coast, AC cables are not suited as losses occur over longer distances. The AC transmission cables face resistive, capacitive and inductive losses, of which most of the electricity is lost as heat through resistance in the power line. To tackle this problem, TenneT introduced its 2GW program where offshore windfarms will be connected to the electricity grid using high voltage direct current (HVDC). The use of HVDC reduces losses in transmission lines to around 2 to 3 percent compared to 5 to 10 percent in AC transmission lines (Berthou, 2020). The 2GW program is named after the capacity of each offshore converter station, which amounts to 2 gigawatts. *Figure 1* provides a schematic overview of the transportation of electricity from the windfarms to the grid. The 66kv AC electricity produced by the wind turbines will be transformed to 525kv and converted to DC in the offshore converter stations. From this point, a single HVDC cable connects the offshore converter station to land where the electricity is transformed to AC and converted to 380kv to match the European high voltage electricity grid. According to TenneT, their 2GW program provides a sustainable alternative as resources and electricity losses are reduced in the offshore connection systems.

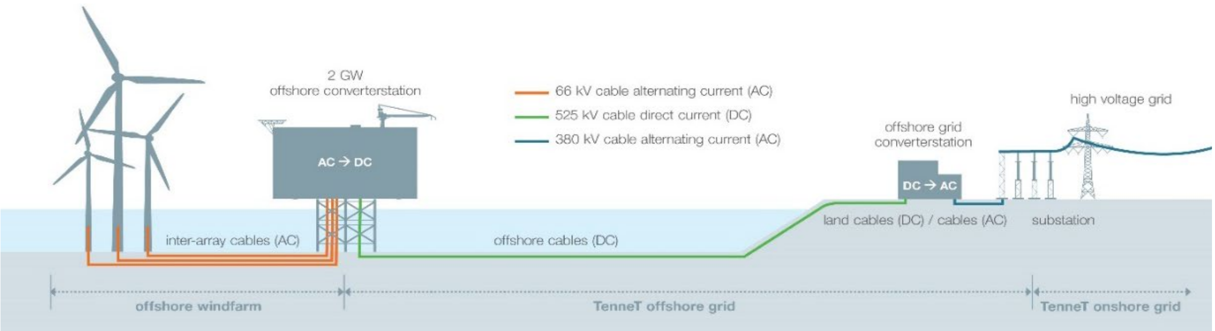

Figure 1. Schematic overview of the 2GW project by TenneT

1.1 Problem identification

Wind farms are connected to the electricity grid during most of its lifetime. To ensure safety, the wind turbines can be disconnected from the electricity grid for maintenance or emergencies. To be able to connect and disconnect the windfarms to the electricity grid, a switchgear mechanism is required. The switchgear is used for switching, controlling, and protecting the electrical power systems, where switching refers to connecting or disconnecting electrical circuits. Switchgear also controls the flow of electrical power, ensuring the direction of power without overloading parts of the system. Additionally, the switchgear protects the system from faults by automatically disconnecting broken sections of the system, preventing damage to equipment or risk to personnel. There are two commonly used types of electrical switchgear, namely Air Insulated Switchgear (AIS) and Gas-Insulated Switchgear (GIS). Due to space-constraints, the offshore converter station makes use of GIS as the required size for the installation is reduced by 80 percent compared to AIS (Kamthe & Bhasme, 2018). In addition, the installation and operating costs for GIS are lower, and equipment is easier to maintain (Chint, 2022).

The commonly used gas inside a GIS is sulphur hexafluoride (SF_6), which is preferred over other gases because of its technical performance. SF_6 has high dielectric strength and arc-extinguishing properties which helps to withstand high voltages and protect equipment. However, despite its technical advantage, SF_6 raises significant environmental concerns because it is the most potent known greenhouse gas. For this reason, alternatives need to be identified which have equivalent functionality, safety, reliability, economic potential as well as environmental superiority (Uchii et al., 2023). The alternatives to SF_6 must comply with these specific requirements, some of which are established by regulations, while others arise from practical implementation. However, no alternative gaseous insulator was discovered which has the benefits of SF_6 and outperforms the gas in terms of environment-friendly properties (Ullah et al., 2020).

SF_6 has the highest Global Warming Potential (GWP) of all greenhouse gases making it 24,300 times as harmful compared to CO2 over a 100-year timescale (IPCC, 2023). According to Kovács et al. (2017), the atmospheric lifetime of SF_6 is about 1278 years, and its only known natural sink is destruction at high altitudes. Consequently, the current presence of SF_6 in the atmosphere equals the total emissions since the start of the industrial era. According to Preisegger et al. (2000), 70 to 80 percent of the global SF_6 production is allocated to power transmission and distribution equipment. The total worldwide emittance of SF_6 is equivalent to 220 billion kg of CO_2 or 0.6% of global emissions. To put this into perspective, this equals the emittance of 50 typical coal power plants (Hitachi Energy, 2024). The total use of SF_6 in the Netherlands is about 175,000 kg, of which 0.51% leaks on a yearly basis (Siemens, 2016). This leakage is equivalent to 21,4 million kg of CO_2, representing 0.0135% of the total annual greenhouse gas emissions in the Netherlands. Although this is a relatively small percentage, fluorinated greenhouse gas emissions are rising since 1990, in contrast to other greenhouse gases. To reduce emissions from fluorinated greenhouse gases, the European Parliament announced Regulation (EU) 2024/573. The regulation states that operation of fluorinated greenhouse gases shall be prohibited from 1 January 2028 for electrical switchgear from 52 kV up to and including145 kV, and 1 January 2032 for electrical switchgear of more than 145 kV. To ensure that future offshore energy can be connected to the grid, alternatives to SF_6 are required.

1.2 Knowledge gap

Since the implementation of SF_6 in high voltage applications there have been environmental concerns. Research has been performed since the 1980's to find gases with superior insulation characteristics to SF_6. Research on this topic declined as no better performing alternative was found, until the research focus shifted from technical performance to environmental impact reduction in recent years (Franck et al, 2021). Alternatives to SF_6 have been successfully implemented in low-voltage and medium-voltage switchgear, achieving a significant reduction in GWP compared to SF_6. According to ENTSO-E (2024), high-voltage switchgear without the use of SF_6 is situated in technology readiness level 6, meaning that a prototype is in a relevant environment. TenneT has several vendors exploring various options for alternatives to SF_6. Therefore, the primary knowledge gap lies in evaluating the implementation of SF_6 alternatives in offshore converter stations. As a result of a literature review, a notable shortage of detailed studies and guidance on this topic was observed, making it difficult for manufacturers and TenneT suppliers to make well-informed decisions. For the development of future wind farms, research on this topic is essential to ensure that construction of offshore wind energy projects can proceed with regulatory compliance, thereby contributing to climate objectives.

1.3 Link to CoSEM program

The CoSEM master's program focusses on designing systems in complex socio-technical environments. These complex socio-technical environments are systems where social and technological components influence each other, shaped by interactions between institutions, technology, and processes. To understand these interactions, the CoSEM master's program first provides courses to understand each individual lens, after which the institutional, technological and process lens are combined in the course 'Design Project'. In the course 'Law and Institutions', it was learned to apply the institutional lens to work with the law as a system. This was done by understanding legal instruments which are used in institutional frameworks. By defining legal borders of the design space, relevant laws can be identified and applied to the socio-technical system. The technological lens was described in the course 'Design of Integrated Energy Systems', which focussed on improvements to energy systems though the integration of multiple models and frameworks. The performance of an integrated energy system is affected by core processes, and it demonstrated that using multiple models better presented the technological system. The understanding of the entire value chain was described, considering both short-term and long-term dynamics. Moreover, the course highlighted the need to address complexities in multi-actor systems. The interactions in multi-actor systems relate to the process lens, which was taught in the course 'Managing Multi-actor Decision Making'. The course emphasizes how system dynamics evolve by the decision-making of individual stakeholders. The course provided strategies to shape and manage decision-making in systems with multiple stakeholders, each having different perspectives. In the fourth and final quarter, the course 'Design Project' focussed on framing a complex design problem as a much-needed intervention. For the successful implementation of this intervention, product designs were created following interviews from a technical, institutional, and process perspective, leading to multiple design outcomes. These outcomes were combined to obtain an integrated design were the technical system, institutional arrangements, rules, and a timeline for a decision-making process were both communicated and evaluated. As a second course in the fourth quarter, 'Research Challenges' taught how to develop evidence-based insights through literature reviews. A systematic approach for the execution of a literature review prepared for the master thesis.

In this thesis, the skills acquired through the CoSEM master's program are applied to evaluate alternatives for the use of SF_6 in electrical switchgear within a socio-technical environment. This intervention is caused by adaptations in the institutional framework with the implementation of Regulation (EU) 2024/573. Using the institutional lens, the legal borders of the system are defined, and relevant laws and regulations are described in this thesis. To gain a better understanding of the technological scope, alternatives are identified and evaluated using multiple frameworks. This process includes comparing the technological characteristics of the alternatives, evaluating their potential for future implementation, and analysing the total emissions. The process lens is applied to analyse the stakeholders in the system. Since TenneT does not have the necessary human resources to implement the 2GW program, it is managed through contractors and sub-contractors, each with their own interests and expertise. Interviews are conducted to understand stakeholder perspectives on the adoption of SF_6 alternatives. To better understand the technical and institutional lens, a literature review is performed. The courses in the CoSEM curriculum are reflected in this study, which integrates, technical, institutional, and process perspectives to identify the best alternatives to SF_6.

1.4 Thesis outline

The thesis is structured as follows: Firstly, Chapter 2 describes the research approach, from which the research question and sub-questions follow, with the applied research methods. Chapter 3 describes the decision context with relevant regulations, the institutional design, the platform design, and relevant stakeholders. In chapter 4 the criteria are described which are being applied for the evaluation process. Chapter 5 defines the alternatives, whereafter evaluation takes place. Chapter 6 describes the drivers and challenges that effect the adoption of alternatives. Chapter 7 serves as the conclusion of the thesis, encompassing a discussion, policy recommendations and suggestions for further research.

2. Research approach

In this chapter the research question is described, followed by the methodological framework that is applied in this thesis. The research approach integrates both qualitative and quantitative methods to understand technical, institutional and process perspectives of the system. Following from the knowledge gap, alternatives with a reduced environmental impact to SF_6 must be evaluated. From a technical perspective, not every gas is suitable for implementation in electrical switchgear, as each gas has specific characteristics. Additionally, from a process perspective, the alternatives must align with stakeholder perspectives and be feasible for implementation in offshore converter stations. As the development of offshore wind energy is still in its early stages, consideration of innovations in converter stations is necessary. Moreover, regulatory frameworks are in place to guide these technologies which need to be considered from an institutional perspective to ensure regulatory compliance.

2.1 Research question and sub-questions

The exploration for more sustainable alternatives for the application in high voltage switchgear, considering short-term and long-term applicability and regulatory compliance results in the following research question:

What is the most viable alternatives to SF_6 in high-voltage switchgear for offshore converter stations, and how can its implementation be aligned with future platform developments and regulatory frameworks?

The primary research question will be addressed through a series of sub-questions outlined below. A description of the relevance and background of the sub-questions is provided.

1. *What is the decision context within which TenneT operates in the offshore wind industry?*

The first sub-question aims to define the system from an institutional and a process perspective. The institutional boundaries are defined and relevant rules and regulations are described which impact the implementation of electrical switchgear in the offshore converter stations. To understand the system from a process perspective, the relevant stakeholders are described in relation to TenneT and the 2GW project. The information required to answer the first sub-question will be acquired through the performance of interviews and literature research.

2. *What are the key criteria to consider when evaluating the viability of alternatives to SF_6 for use in gas-insulated switchgear?*

To evaluate alternatives to SF_6 their characteristics must be compared. Uchii et al. (2023) define the requirements for SF_6 alternatives as having equivalent functionality, safety, reliability, economic potential, as well as environmental superiority. These overarching requirements are divided into measurable components, which are described as criteria. Scaling down to measurable characteristics allows for comparing and evaluating alternatives. The criteria are identified through literature research, and then validated and supplemented through an interview with a participant from TenneT.

3. *What are the alternatives to SF_6 and how do they perform when evaluated against the criteria?*

Once the criteria are identified, the third sub-question focusses on applying these criteria to evaluate potential alternatives. Initial literature research is conducted to identify these alternatives, after which they are described. Subsequently, each alternative is scored based on the established criteria and assessed using a multi-criteria evaluation. Finally, the most viable alternatives are presented.

4. *What are the key drivers and challenges influencing the adoption of SF_6 alternatives in the offshore wind sector?*

The fourth sub-question focusses on the implementation of the identified SF_6 alternatives, with a primary focus on the process perspective. While the third sub-question mainly addresses the technical perspective, the fourth sub-question addresses market dynamics and stakeholder perspectives that influence adoption. To explore key drivers and challenges which affect offshore converter station construction, interviews with relevant stakeholders are conducted. Additionally, literature research is performed to obtain information on market trends and stakeholder decisions that could impact future implementation.

5. *How do the environmental impacts of the alternatives compare during construction and operation?*

The intervention to the current system design is based on the environmental concerns. The alternative should comply with reduced GWP, but an alternative design could impose increased emissions in the lifecycle of the switchgear. For this reason, sub-question 5 aims to define the environmental impact of both the alternative gas as the installation through an environmental impact comparison, including the manufacturing and use phases. Data for this analysis will be obtained through literature research and information provided by constructors.

2.2. Research method

In this section, the methods applied in this study are described and the subsequent execution is outlined. Identifying the most viable alternative to SF6 involves multiple dimensions, which include technical viability, alignment with evolving platform developments, and adherence to regulatory frameworks. This multifaced nature necessitates an approach that integrates multiple types of data and insight to provide a complete evaluation.

The research begins with an exploration of the decision context in Chapter 3, which involves literature research to understand core market dynamics and semi-structured interviews to gather expert opinions on SF_6 alternatives and their application in offshore platforms. This interview format is chosen to supplement literature research findings with market specific experiences, challenges, and expectations from those directly involved in the field. The semi-structured nature allows flexibility to address emerging themes while maintaining focus on predefined questions to answer the sub-question. By engaging with professionals who have hands-on experience with gas-insulated switchgear and offshore infrastructure, the study aims describe the decision context both from a technical and a stakeholder perspective.

Participants for the interviews are selected based on recommendations from contacts within TenneT. The participants are involved in the 2GW project, which ensures relevant knowledge and experience, enhancing the credibility of the collected data. Prior to conducting the interviews, participants receive an informed consent form, which outlines the purpose of the study, how the data will be used, and their rights concerning confidentiality and withdrawal. This ensures ethical compliance and transparency in the research processes. All interviews will be transcribed with the consent of the participants. The transcription will serve to gain insights and derive citations, ensuring the accuracy of the information presented in the thesis. The transcriptions of the interviews are presented in Appendix E.

Subsequently, Chapter 4 focusses on the establishing the criteria to evaluate the alternatives. The criteria will be identified trough literature research. Multiple aspects of potential alternatives are considered, and a selection of the key criteria will be outlined. An interview is conducted to ensure that all key criteria are covered. The key criteria will be discussed in more detail to provide better understanding in the characteristics of the most viable alternative to SF_6. This qualitative data supports the multi-criteria evaluation in Chapter 5, in which each alternative is evaluated based on the key criteria.

Chapter 5 focuses on obtaining numerical values to the criteria of alternatives. These values are acquired through extensive literature research. This phase establishes a solid foundation, providing a factual base for the evaluation of alternatives.

Subsequently, Chapter 6 delves deeper into the practical application of the alternatives for current and future offshore converter stations. Semi-structured interviews are conducted to understand both the . Stakeholders, including manufacturers, regulators, and environmental advocates, have vested interests in the outcomes. The qualitative data also supports the prospective analysis, which examines key drivers and challenges for the construction of future platforms. This approach ensures that risks and opportunities that could affect the implementation of alternatives are considered.

A second research method applied in Chapter 6 is the environmental impact comparison. The results of this method are crucial for the understanding of the sustainability of the alternatives. This method is based on the Life Cycle Assessment method, though it does not entail a complete life-cycle assessment due to time constraints when combined with the other research methods. The adapted approach of the environmental impact comparison focuses on the elements that contribute most significantly to total emissions, adapting the analysis, while still providing valuable insights into the environmental impact of each alternative.

2.3 Research flow diagram

A comprehensive overview of the applied methods for each chapter is provided in *Figure 2.3* below. The chapters are subdivided in multiple steps, under which the applied method is shown. The sub-questions are addressed through the chapters as shown in the research flow diagram.

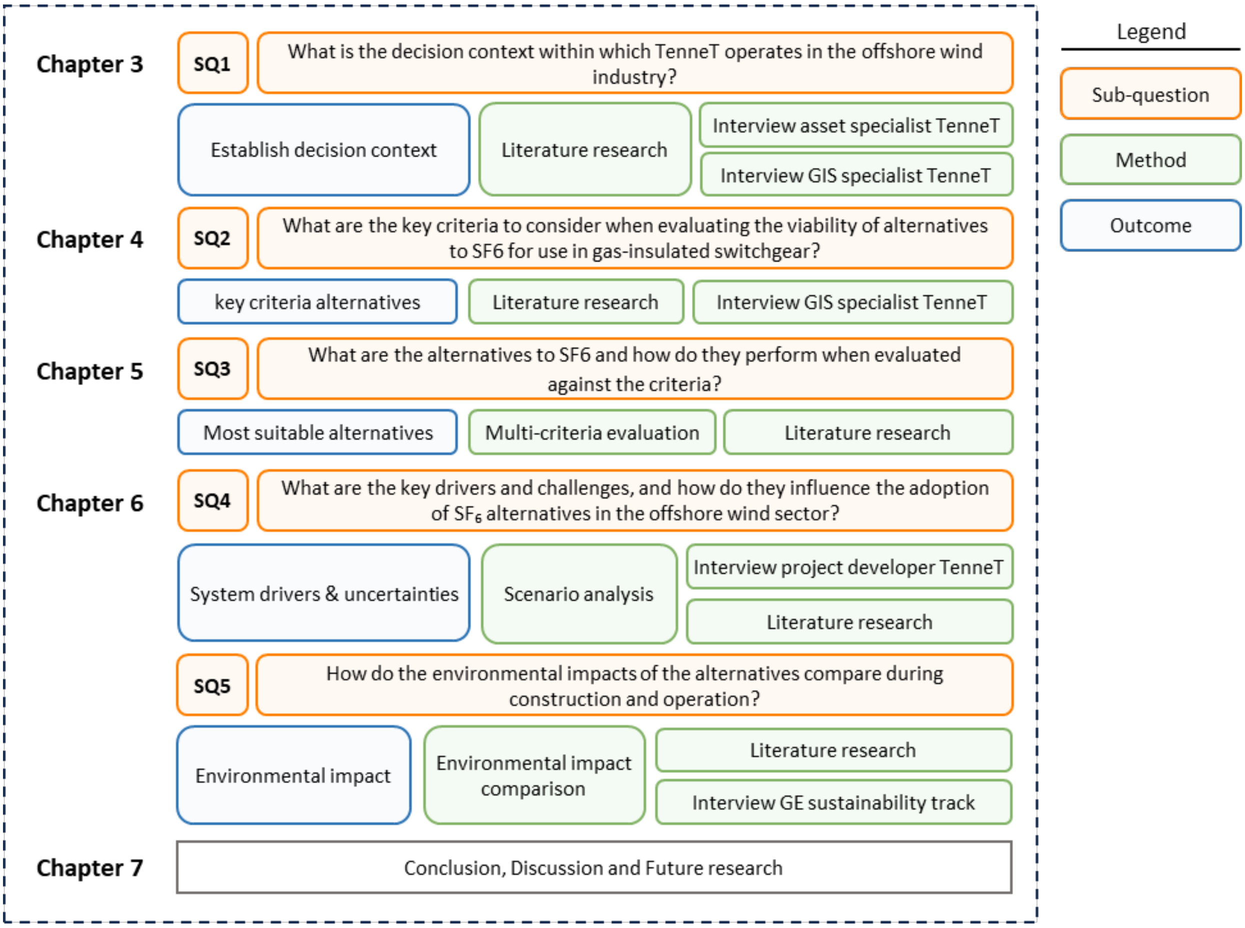

Figure 2.3. Visual representation of the applied research methods in a research flow diagram.

3. Decision context

This chapter describes how the offshore wind energy production in the North Sea is organized and which stakeholders are involved. This chapter lays the foundation to understand dynamics and explore improvements in the system. The information presented in this chapter was gathered through literature research and two interviews. The first interview is performed with a TenneT employee with the job function of offshore development advisor, who is referred to in this study as participant I. The second interview is conducted with a TenneT employee with a job function in offshore GIS installations and is referred to as participant II. The interview provides in depth clarification for constructors and technical requirements for GIS installations. With the use of both interviews, the role of TenneT within the 2GW program is clarified. This chapter is outlined as follows, first, relevant regulations to the construction and design of electrical switchgear is described (3.1). Then, the role of TenneT as project owner is further explained with the division of multiple clusters (3.2). The design of the platform is described to understand the role of the electrical switchgear in the system (3.3). The contractors that are assigned to the construction of the platforms are described in 3.4, after which sub-question 1 is answered (3.5).

SQ1: What is the decision context within which TenneT operates in the offshore wind industry?

3.1 Regulations

The design and construction of electrical switchgear is subject to multiple environmental and energy efficiency standards, both in terms of the gas applied inside the switchgear and the sustainable design of the installation itself. Restrictive use of SF_6 was first presented during the Kyoto protocol in 1997, where the gas was identified as one of the most prominent gases that contributed to climate change. In 2009, directive 2009/125/EC entered into force, creating standards for a sustainable design of electrical equipment. More recently, regulation (EU) 2024/573 restricted not only the use of SF_6, but also sets standards for alternative sustainable gases applied in electrical switchgear. Together, these regulations shaped a transformation in the switchgear industry, focussing on innovative practices and environmentally sustainable technologies. The impact of each regulation is presented in more detail in this chapter.

3.1.1 Kyoto Protocol

The Kyoto protocol was established in 1997 during the Conference of the Parties to the United Nations Framework Convention on Climate Change in Kyoto (United Nations Framework Convention on Climate Change, 1997). This protocol aims to reduce the emittance of greenhouse gases using enforceable targets. All countries in the European Union take part in the protocol and agreed to the terms and conditions. In addition to the EU, industrialized nations with high greenhouse gas emissions like the United States, Russia, Japan, and Australia also agreed to the protocol. Each participating country agreed to specific greenhouse gas reductions or limitations between 2008 and 2012. For most European countries, a reduction of 8 percent compared to the emittance levels of 1990 has been agreed upon. In the list of greenhouse gases, four gases including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and sulphur hexafluoride (SF_6), along with the molecule groups hydrofluorocarbons (HFCs) and Perfluorocarbons (PFCs) were identified to be reduced. For the installation of electrical switchgear, the reduction of SF_6 has the highest impact, as this is the gas applied in most high voltage switchgear.

3.1.2 Directive 2009/125/EC

Directive 2009/125/EC, commonly referred to as the Eco-design Directive, was implemented to enhance a sustainable and circular economy. This directive is relevant to the construction of electrical switchgear as mandatory requirements were defined to enhance the sustainable design and energy efficiency in electrical appliances. The primary goal of the directive is to minimize the ecological footprint of products by focusing on the total emissions of the product lifecycle. The directive functions as a general standard for sustainable production of goods and does not overrule other EU legislation concerning environmental protection. Specifically, in Article 1, Section 4 it is stated that: “This Directive and the implementing measures adopted pursuant thereto shall be without prejudice to Community waste management legislation and Community chemicals legislation, including Community legislation on fluorinated greenhouse gases” (European Parliament & Council, 2009). This provision ensures that the Eco-design Directive does not override or interfere with other critical regulatory frameworks, including regulations on fluorinated greenhouse gases. Such integration is crucial for maintaining a coherent and comprehensive EU environmental policy.

3.1.3 Regulation (EU) 2024/573

According to Regulation (EU) 2024/573 (European Parliament & the Council of the European Union, 2024), fluorinated greenhouse gases account for 2.5% of the total greenhouse gas emissions in the European Union and have doubled between 1990 and 2014, in contrast to the decrease observed in other greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC) stated in its 2021 Special Report that a global reduction of fluorinated greenhouse gas emissions of up to 90% by 2050 is necessary, compared to 2015 levels. As a result, the European Parliament turned Regulation (EU) 2024/573 on fluorinated greenhouse gases into force on 7 February 2024. According to Hitachi (2024), the United Kingdom and the United States of America are preparing similar regulations. The relevant articles of Regulation (EU) 2024/573 for this research are provided in *Appendix A.3* and are visualized in Figure 3.1.3. The implementation of the regulation establishes three distinct markets. The first market is the current one where there is no limit to the GWP. The second market entails alternatives with a GWP between 1 and 10000, and the third market for alternative gases ≤ 1 GWP. Market 2 acts as a transition market to prevent monopolies. This is a two-year transition period, after which a monopoly may be formed. This is presented in Figure 3.1.3 with the timeline and the allocated markets. The Commission publishes a report on the 1st of January 2030 regarding the possible excessive reduction of competition in the market for high voltage electrical switchgear of more than 145 kV or more than 50 kA short circuit current.

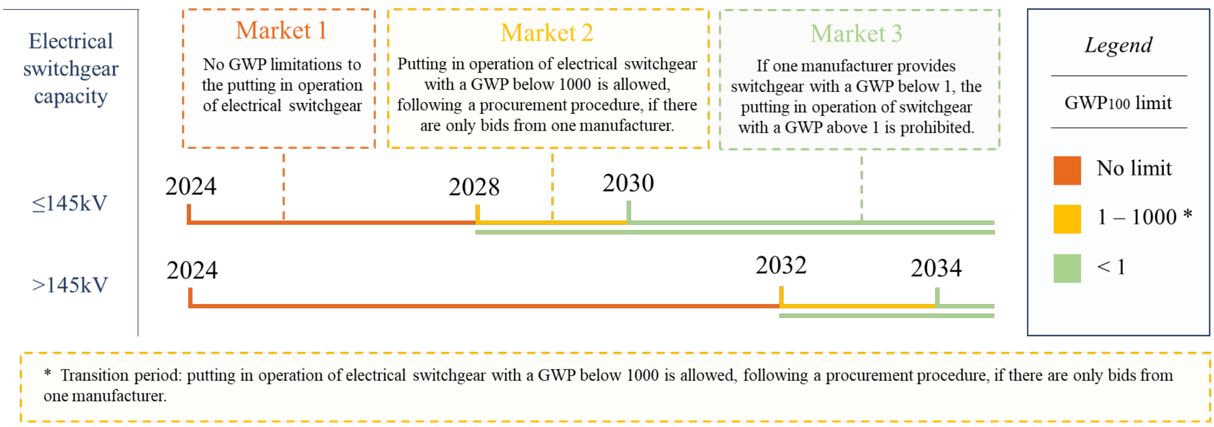

Figure 3.1.3. Timeline for reducing high-voltage switchgear GWP under Regulation (EU) 2024/573

3.2 System context 2GW program

Defining alternatives for SF_6 in gas-insulated switchgear is dependent on the system context. Policy choices, stakeholder decisions, and the internal organization of TenneT define both the opportunities and boundaries of the system. For this reason, it is important how these structures are organized and to analyse its interactions. Starting from a project overview, the policy decisions and the internal organization of TenneT is described. In the following sections, a closer look is taken to obtain insights into the various clusters of the 2GW program and the relation between the Dutch and German organization. The chapter concludes with stakeholder interactions that are most important for the construction and implementation of GIS on offshore converter stations.

3.2.1 Development plans for offshore wind energy by TenneT

In the Paris climate agreement, the ambition is stated that EU member states reduce their CO_2 emissions by 55% compared to 1990 levels. According to these goals, the Netherlands should produce 49 TWh from offshore wind energy. To realize this, it is calculated that a capacity of 11.5 GW is necessary (Rijksoverheid, 2022). Offshore wind energy is expected to become an important energy source to reduce CO_2 emissions and therefore the Dutch Government decided to expand the planned capacity to 21 GW in 2033. According to Participant I, this process starts with the Exploration of Offshore Wind Grid Connection (Verkenning Aanlanding Wind Op Zee, VAWOZ). In this process the onshore energy demand, suitable landing locations, and possible cable routes with their costs and climate impact are described. The VAWOZ process for the realization of wind energy in 2033 was announced in 2021 by the minister of Economic Affairs and Climate, after which a development framework was set up. This development framework describes the locations for grid connection, for which TenneT is responsible. Rijkswaterstaat decides on the site selection for offshore windfarms, which are shown in Figure 3.2.2 (1). The Rijksdienst voor Ondernemend Nederland (RVO) provides a permit, after which the tender procedure starts. Although not all sites already started the tender procedure, TenneT started the realization of offshore substation platforms as these locations have been allocated. Until 2033, the 2GW program will reach a total capacity of 16 GW across 8 sites. For the realization of the platforms, TenneT started a tender in July 2021, after which framework agreements were signed with two constructors in the Netherlands and three in Germany, which will be further elaborated on in section 3.4.

3.2.2. Dutch project clusters

For the internal organization of TenneT, the connection of offshore wind farms is grouped in project clusters. In the tender procedure of Rijkswaterstaat, eight sites were allocated for the production of offshore wind energy, each with a capacity of 2 GW. These sites all require an offshore converter platform, which were set out as a tender by TenneT. Following the tender, two consortiums are tasked with the realization of the offshore platforms in the Netherlands. Petrofac and Hitachi Energy (PHE) form one consortium, presented in red, while General Electric and Seatrium (GSC) comprise the other, shown in blue, as shown in Figure 3.2.2 (1). The General Electric Seatrium Consortium is responsible for constructing three platforms with a total capacity of 6 GW, that will be connected onshore to the electricity grid at the Maasvlakte Rotterdam. In this consortium, General Electric handles the electrical systems, including the gas insulated switchgear, and Seatrium is responsible for constructing the physical platform. The remaining five platforms are allocated to the Petrofac Hitachi consortium, of which two platforms are connected to Borssele, two to Eemshaven, and one to Geertruidenberg. Other stakeholders are involved in laying the HVDC cables on the seabed and constructing the onshore converter station. A schematic overview of the Dutch project clusters is presented in Figure 3.2.2 (2). The findings of this study aim to offer insights relevant to all the clusters within the 2GW program.

Figure 3.2.2 (1). Planned developments and platform constructors for the 2GW program in the Netherlands.

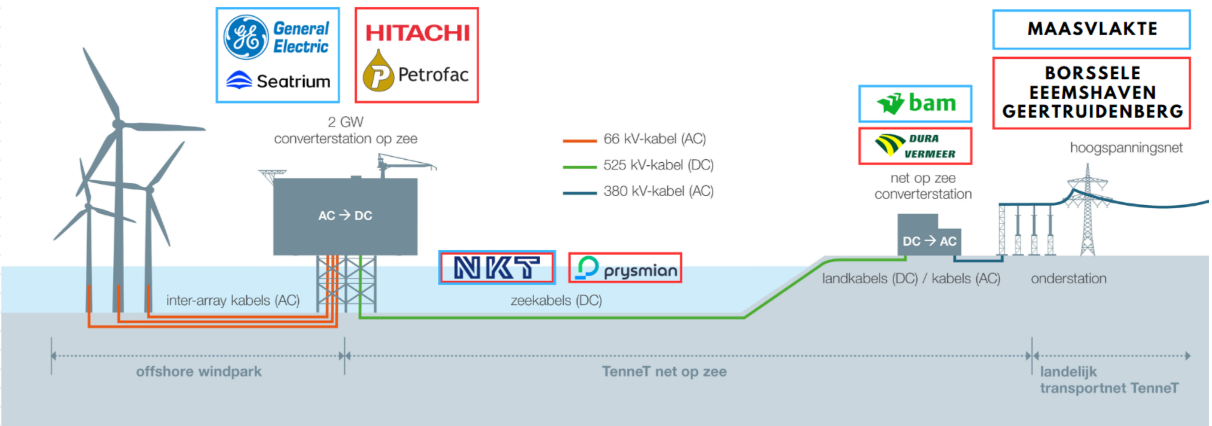

Figure 3.2.2 (2). Schematic overview of Dutch offshore wind energy project clusters and stakeholders.

3.2.3. German project clusters

The construction of the 2GW program is both a Dutch and a German project. In 2009, the electric utility company E.ON transferred its high-voltage grid and the associated organizational units into the new company Transpower, which was taken over by TenneT on the 1st of January 2010 (Algemene Rekenkamer, 2015). With this takeover, TenneT became the first European transmission system operator with high voltage network in multiple countries. In the 2GW program, the German side of TenneT plays a crucial role for the Dutch offshore grid expansion through knowledge spillovers and cost reductions because of economies of scale. To establish collaboration, there are quarterly meetings for coordination, but as the offshore departments are externally focused, complexity to the alignment process is added (Participant I). Comparable to the VAWOZ in the Netherlands, the German offshore projects follow the Flächenentwicklungsplan to identify and designate areas in German maritime waters suitable for offshore wind energy projects.

The allocation of platform construction in Germany involves several collaborations and are shown in Figure 3.2.3. Here, three consortiums are allocated to the construction of six offshore platforms. Top-site constructor Hitachi, in partnership with jacket constructor Petrofac, is responsible for the LanWin5 platform, which connects to Rastede. General Electric, as in the Netherlands, oversees the top-side construction of platforms but collaborates with McDermott (GEM) for the jacket construction of two platforms connected to Unterweser. Siemens, the third top-side constructor, operates exclusively in Germany. Siemens has partnered with Dragados (2OC) to build one platform connected to Heide and two platforms linked to Wilhelmshaven.

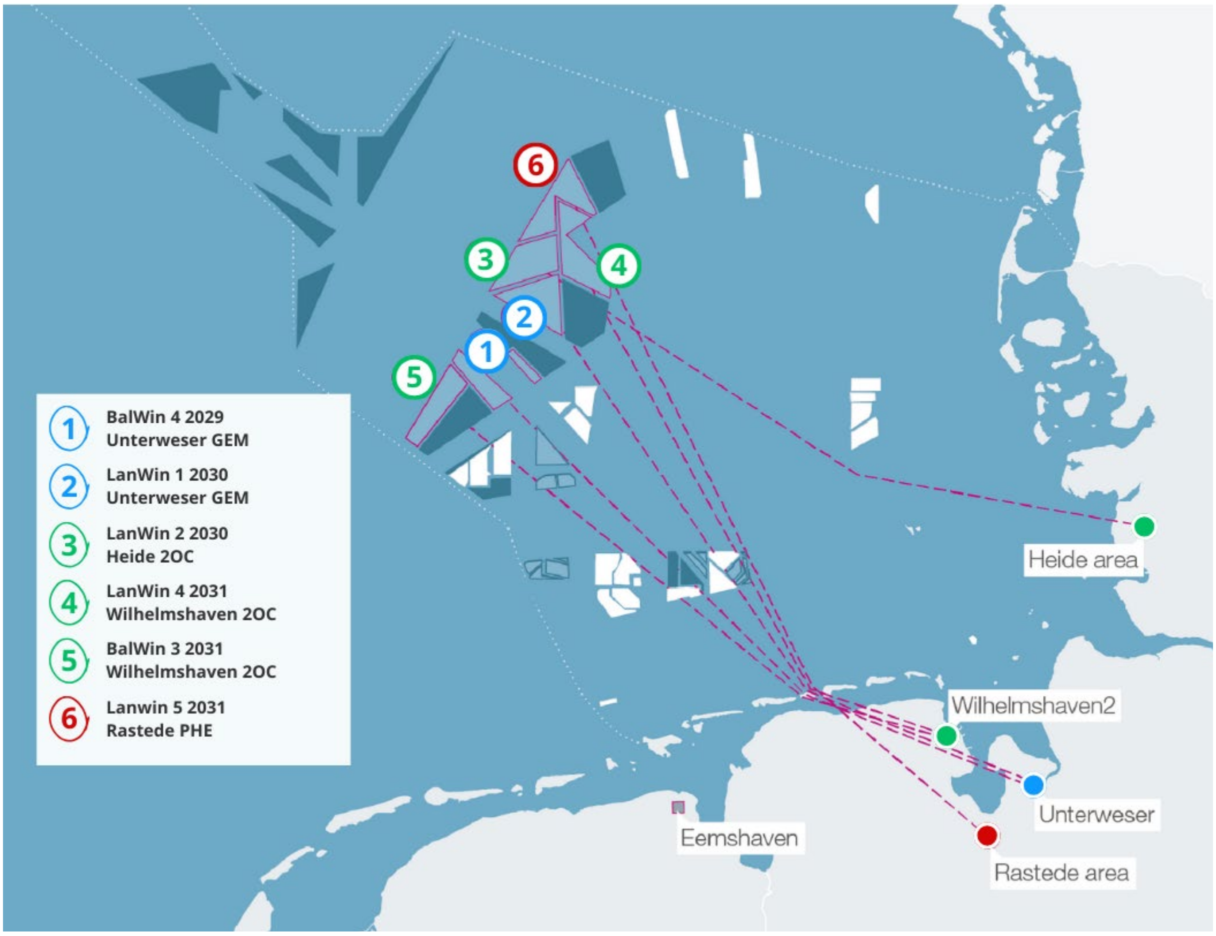

Figure 3.2.3. Planned developments and platform constructors for the 2GW program in Germany.

3.3 Platform design

To understand the role of the electrical switchgear, understanding of the platform outlook is required. The offshore converter stations are designed to provide a maximum capacity of 2000 MW. The core function of the offshore platform is to convert the electrical power generated by offshore wind turbines from alternating current to direct current. A cross-section of an offshore converter station for the 2GW program is presented in Figure 3.3 (1). The functions of all components within the platform are detailed here in sequential order. First, the AC cables of the wind turbines, with a capacity of 66kV, are linked to the platform via cable pulls. The offshore wind turbines themselves have capacities ranging from 10 to 15MW, which means that there are 133 to 200 wind turbines connected to the platform. The incoming cables are grouped and connected to the electrical switchgear to manage multiple incoming streams of electricity. A more detailed explanation of the electrical switchgear room is provided in section 3.3.1. After passing the electrical switchgear room, the voltage level is increased from 66kV to 306kV by the transformer. The AC electricity is then converted to DC in two separate voltage source converter halls, resulting in a neutral and either a DC-positive or DC-negative cable. These cables then proceed to the valve reactor, which mitigates fault currents in the event of DC faults and manages circulating currents in the converter. As presented in Figure 3.3 (1), which shows a cross-section of the platform, this setup is mirrored on both sides of the platform. The two neutral cables are joined, creating a set of three HVDC cables: one DC-positive, one DC-negative, and one neutral. Along with a fibre optic cable for data communication and control signals, these cables are bundled into one single composite sea cable.

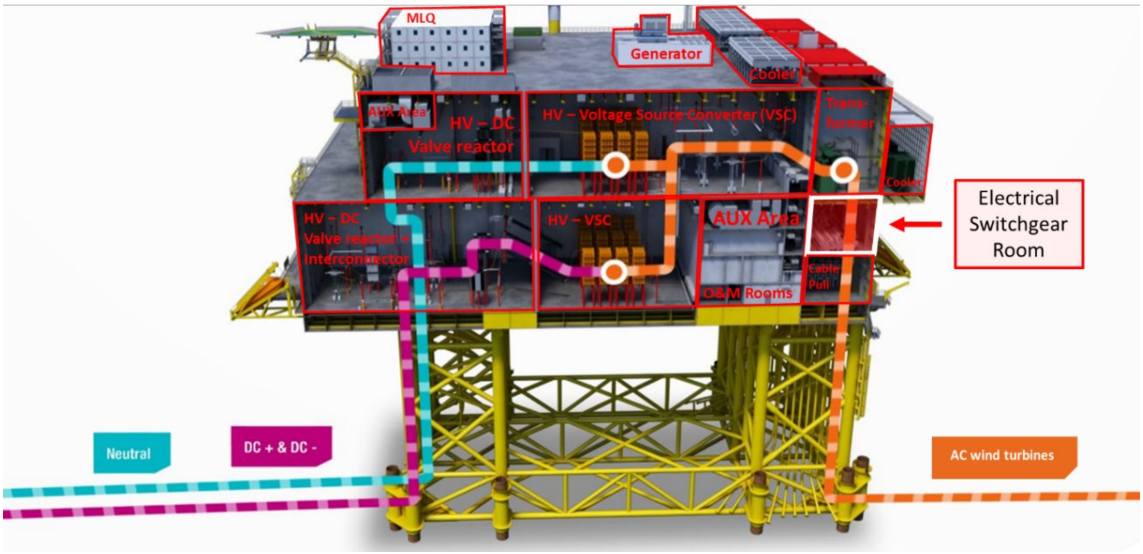

Figure 3.3 (1): Cross-section of an offshore converter station for the 2GW project.

Once the sea cable reaches onshore, the DC electricity is converted back to AC at the onshore converter station, where it is then adjusted to align with the Dutch 380kV electricity grid. Depending on space availability, the electrical switchgear installed may be either AIS or GIS. From this point, a 380kV AC cable connects to the onshore station of TenneT, where the project clusters are connected. Below, Figure 3.3 (2) provides a schematic overview detailing the electrical components from the wind turbines to the electricity grid.

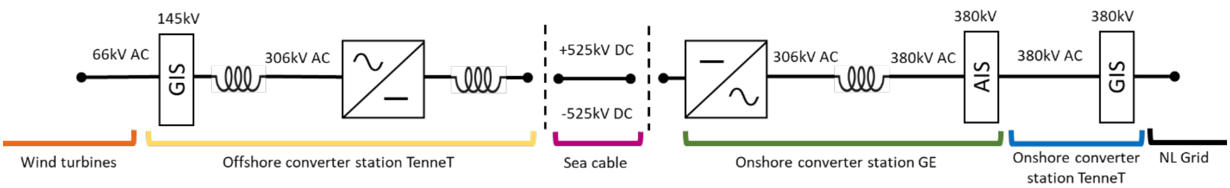

Figure 3.3 (2): schematic overview of electrical components within the 2GW scope.

3.3.1 Electrical switchgear room

In the electrical switchgear room, the power generated by offshore wind turbines is managed to ensure that the system can safely continue operations, even during maintenance. This section provides an overview of how the switchgear organizes both incoming power from the wind turbines, and outgoing power to the transformer and auxiliary systems. Figure 3.3.1 visually represents this arrangement, showing that the setup includes 28 incoming groups from the wind turbines and 12 outgoing groups to the transformer and auxiliary. The switchgear is divided into four blocks, each consisting of ten groups: seven for wind turbines, two for the transformer, and one for auxiliary systems. The auxiliary systems support operations like control and monitoring, cooling, fire safety, lightning, and communication. The layout across all four blocks is detailed on the right side of Figure 3.3.1, summing up to a total of 40 groups, and therefore 40 electrical switchgear installations.

To support a total system capacity of 2 gigawatts, the wind turbines are organized into 28 groups, each producing slightly under 100MW. These groups are referred to as bays. The electrical switchgear needs to match the 66kV voltage level of the incoming turbine cables. Although the closest standard switchgear available on the market is 72,5kV, the transformer requires a 145 kV switchgear to operate. Consequently, a 145kV switchgear is used across all offshore converter stations.

For enhanced reliability, connections to transformers in blocks 2 and 3 are cross-linked. This setup ensures that if one side fails, whether block 1 and 2, or 3 and 4, the system is still able to provide half of the power (Participant II). If the blocks were not cross linked, the system would be limited to provide electricity to either the negative or the positive pole, resulting in system failure. The cross-linked setup is presented in Figure B1 in Appendix B.

Looking ahead, after the completion of current projects, further expansion in the offshore wind sector is expected. Currently, the wind turbine capacities range between 10 and 15MW, connected via a 66kV inter-array cable to the platform. Projections by Wiser et al. (2021) indicate that offshore turbine capacities will increase to 17MW in 2035, potentially requiring the use of 132 kV inter-array cables to handle higher power output.

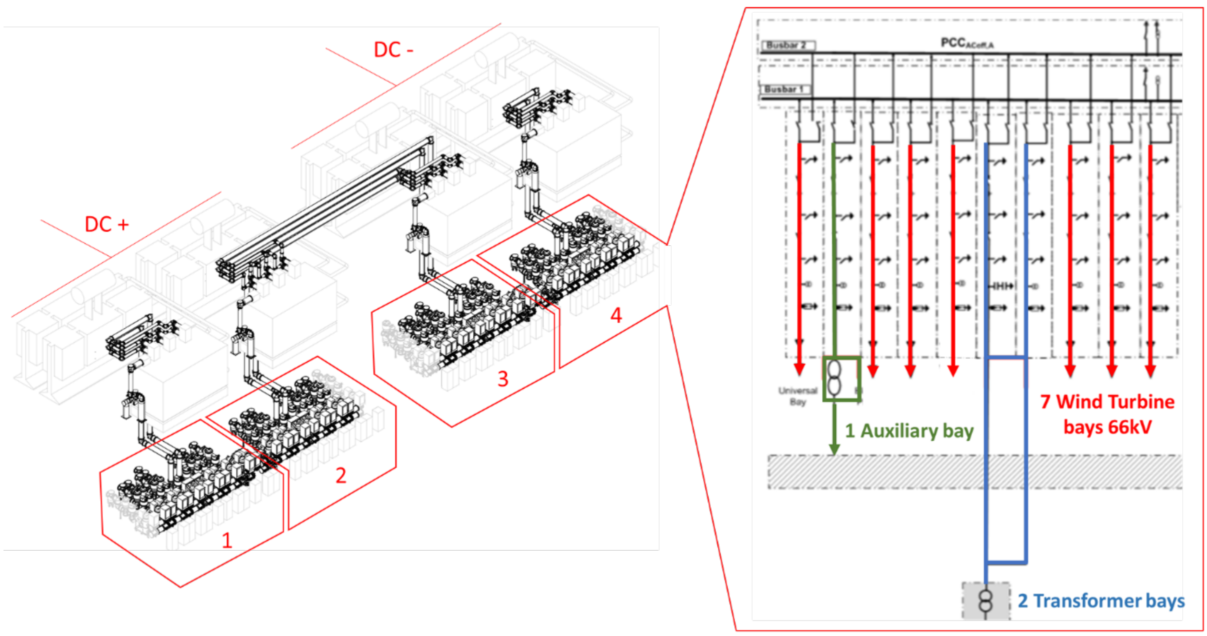

Figure 3.3.1: Electrical switchgear installations on the first-generation offshore platform.

3.3.2 Gas-Insulated Switchgear

This section explains the working principle of a gas-insulated switchgear. First, an overview of the GIS is provided to understand its functions, after which the circuit breaker is explained in more detail as this part ensures the switching mechanism of the GIS. Figure 3.3.2 (1) shows a cross-section of a gas-insulated switchgear on the right, for which the layout is similar for all manufacturers. In the middle, a schematic line diagram is presented for the working principle of the switchgear. On the left side, the individual components are numbered which correspond to both the cross-section and the schematic line diagram. The working principle is described in the order of the list of components.

Busbars 1 and 2 connect the circuit of multiple switchgear installations, as they are placed next to each other in blocks, as shown in Figure 3.3.1. There are two busbars to make sure that if one fails or in case of maintenance, the system continues functioning using the other busbar. The circuit breaker protects the system by interrupting the electrical flow and thereby opening the circuit. The current transformer measures electrical current and provides feedback for protection and monitoring. The function of the disconnector is to provide a visible break to provide safe maintenance. The voltage transformer reduces the voltage level for measurements. The high-speed earth switch is a safety component, to quickly ground electricity. The cable termination is the connection to the following component in the system, which are the wind turbines, the transformers, or the auxiliary systems.

The components that are not presented in the schematic line diagram but shown in the cross-section are the local control cubicle, which houses control and protection devices and is stabilized by the support for control cubicle. The stored energy spring mechanism with circuit breaker control unit provides energy to open and close the circuit breaker rapidly. To prevent electrical flashovers and protect equipment, the switchgear is completely insulated with a gas, which is SF_6 for most switchgear types. Interruption of the electrical flow takes place in the circuit breaker, which also contains a SF_6, or a potential alternative.

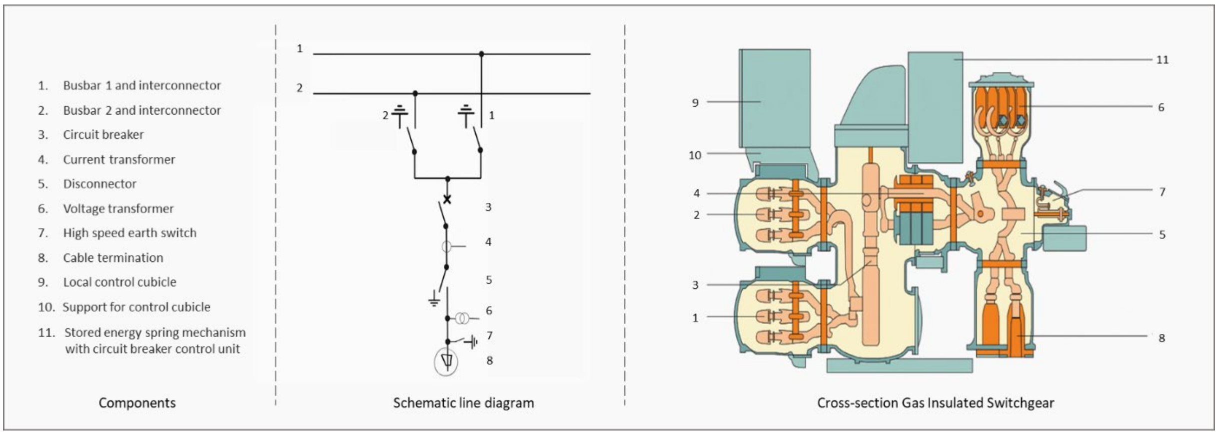

Figure 3.3.2 (1): Adaptation of the schematic outlook of a gas insulated switchgear from Alshahrani (2024).

The working principle of a circuit breaker is presented in three phases in Figure 3.3.2 (2). During normal operation, the circuit breaker is in a closed position as presented on the left side. The live parts are connected to each other, closing the circuit, and allowing electrical flow through the circuit breaker. In case of a fault or during maintenance, the circuit breaker opens quickly by retracting the moving parts. In this way, the contacts get separated, and an electrical arc is formed as shown in the right side of the image. Current is still flowing through the arc which could damage equipment. To interrupt the current flowing through the circuit breaker, SF6 gas is added to absorb the free electrons through which the arc is quenched. Once the arc is quenched, the current becomes zero and the circuit is interrupted.

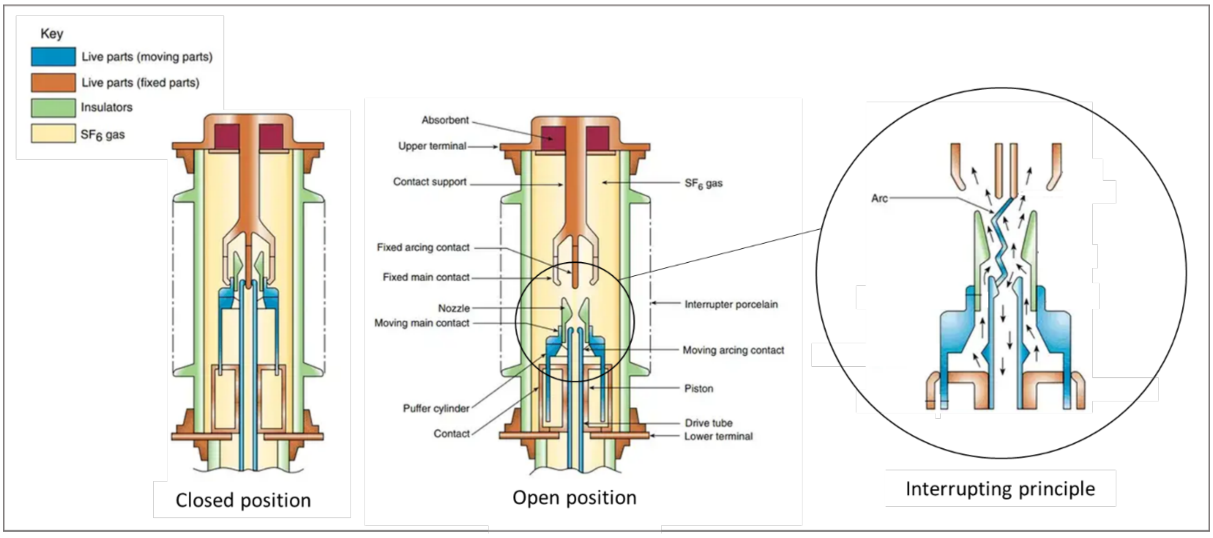

Figure 3.3.2 (2): Adaptation of the working principles of a gas insulated circuit breaker from StudyElectric (2019)

3.4 Platform constructors

The market for high voltage equipment is mainly dominated by General Electric, Hitachi Energy, and Siemens Energy. These three companies have high market shares in Europe and competition is limited. According to participant I, the converter stations are categorized as vital infrastructure, limiting the option for Chinese companies to enter the European market. The three companies will most likely maintain the largest market share in the construction for future platforms with the possibility of a Japanese or Korean company entering the market. With General Electric, Hitachi Energy and Siemens Energy being the contractors for the converter stations, their GIS installation alternatives are discussed in the following sections.

3.4.1 General Electric

General Electric was originally founded by Thomas Edison in 1892 to promote his lightbulbs. Almost 130 years later, in 2020, General Electric split up in three divisions, being GE Healthcare, GE Aviation and GE Vernova (IronFx, 2023). GE Vernova is the contracting side for TenneT with five decades of expertise in gas-insulated switchgear technology. In 2019, GE Vernova introduced their newest GIS installations F35g, with a capacity of 145kV, and F35 with a capacity of 145kV and 170kV (GE Vernova, 2024). The F35g installation replaces SF_6 with g^3 (Green Gas for Grid), which is a mixture of C_4F_7N, O_2 and CO_2, and serves as an SF_6-free alternative for high-voltage applications. This provides flexibility for a more gradual phase out of SF_6, complying with upcoming regulations. GE Vernova ensures that a transition from SF_6 to g^3 can be executed with minimal disruption. The GIS installation is also available for 245kV and 420kV called the B105g and T155g respectively. The higher capacities make it possible to interrupt higher voltages for future platforms when necessary. The GIS installations provided by GE Vernova in the range of 145kv up to 170kV are presented in Table 3.4.3 1.

3.4.2 Hitachi Energy

Hitachi Energy is a globally operating electricity grid constructor founded between 1890 and 1910 (Hitachi Energy, 2025). Hitachi Energy originated from the mergence of three companies, ASEA, BBC and Hitachi. ASEA was a Swedish industrial company specialized in manufacturing electrical equipment. With specialized knowledge they constructed the first High Voltage Direct Current (HVDC) line in 1954. In 1988, ASEA merged with BBC, a company specialized in the construction of GIS and transformers, to become ABB. The company Hitachi was founded in 1910 and became the first general electric machinery manufacturing business in Japan. In 2020 the companies Hitachi and ABB merged to become Hitachi Energy acquiring knowledge in HVDC, GIS and electricity grids. Hitachi Energy constructs SF_6-free high-voltage GIS with capacities in the range of 145kV up to 420kV (Hitachi Energy, 2025b). Recently, Hitachi Energy constructed a 550 kV circuit breaker that can be used in GIS, which could be the first 550 kV rated SF6-free GIS. The portfolio of Hitachi Energy GIS installations in the range of 145kV to 170kV is presented in Table 3.4.3.

3.4.3 Siemens Energy

Siemens Energy originates from 1847, when artillery officer Werner von Siemens in cooperation with Johann Georg Halske founded the firm Siemens & Halske (Siemens, 2025). Over the company lifespan, Siemens focussed on various aspects of energy technology, starting with electric streetlights and dynamos in the late 19th century to high-efficiency power plants and renewable energy systems nowadays (Siemens Energy, 2025). The first SF6 high-voltage circuit breaker was introduced in the European market by Siemens in 1964, offering the possibility to decrease installation size and reduce maintenance (Siemens Energy, 2025a). In 2020, Siemens Energy decided to split off from the parent organization Siemens AG, to establish a better focus on the energy sector. Regarding the insulation and breaking medium of electrical switchgear, Siemens Energy has a different design compared to Hitachi Energy and General Electric. Where the latter two make use of SF_6 or a $CO_2/O_2/C_4F_7N$ gas mixture at high pressure, the SF_6-free circuit breaker of Siemens Energy operates without a gas in a vacuum surrounding. The installation is insulated with clean air at higher pressure levels. The portfolio of clean air and vacuum switching products of Siemens Energy is called the 'Blue' line. Siemens Energy ensures zero F-gases, zero toxicity and no harm to the environment and human health (Siemens Energy, 2025b). The available high voltage vacuum switchgear ranges from 72,5kV to 145kV. The installations are slightly larger and heavier with the characteristics presented in Table 3.4.3.

Table 3.4.3: SF_6 and SF_6-free electrical switchgear portfolio in the 145 to 170kV range of the constructors for the first-generation platforms. The specifications follow from technical brochures: F35g (General Electric, 2019), F35 (General Electric, 2016), 8DN8 (Siemens Energy, 2021), 8VN1 (Siemens Energy, 2021a), ELK-04 (Hitachi Energy, 2021), EconiQ ELK-04 (Hitachi Energy, n.d.)

Supplier	Product	Rated voltage	Insulation	Inter-ruption	GWP	Bay width	Bay height	Bay depth	Bay weight
General Electric	F35	145 kV	SF_6	SF_6	24300	1.0 m	3.0 m	-	-
	F35g	145 kV	$CO_2/O_2/C_4F_7N$	$CO_2/O_2/C_4F_7N$	469-614	0.8 m	2.5 m	3.7 m	-
	F35	170 kV	SF_6	SF_6	24300	1.0 m	3.0 m	-	-
Hitachi Energy	ELK-04	145 kV	SF_6	SF_6	24300	1.0 m	2.8 m	-	-
	EconiQ ELK-04	145 kV	$CO_2/O_2/C_4F_7N$	$CO_2/O_2/C_4F_7N$	469-614	1.2 m	2.6 m	4.0 m	3.4 t
	ELK-04	170 kV	SF_6	SF_6	24300	1.2 m	3.0 m	-.	-
Siemens Energy	8DN8	145 kV	SF_6	SF_6	24300	0.8 m	2.6 m	-	3 t
	8VN1	145 kV	Clean air	Vacuum	0	1.0 m	3.2 m	5.5 m	4.7 t
	8DN8	170 kV	SF_6	SF_6	24300	1.0 m	3.2 m	5.5 m	4.7 t

3.5 Answer to sub-question 1

This chapter aimed to understand the decision-making context within which TenneT operates in the offshore wind industry, by addressing the first sub-question. The findings indicate that the offshore operations by TenneT are strongly influenced by the interplay between stakeholders, regulatory frameworks, and its own institutional structure. The institutional boundaries for the implementation of alternatives to SF_6 are defined by the Kyoto Protocol and EU directives. The regulations require that TenneT, as the project owner, must comply and facilitate coordination with the contracting stakeholders to achieve sustainability goals and match technical requirements.

The institutional design of TenneT for the 2GW project is organized in project clusters, as it is not possible for a single contractor to deliver all the platforms in time. This increases the number of stakeholders, which could potentially lead to delays as multiple perspectives are considered, but it could also facilitate knowledge spillovers between different clusters. It is the responsibility of TenneT to find the most efficient balance between integration and separation of these clusters.

4. Criteria identification

The aim of this chapter is to establish criteria for quantifying potential alternatives to SF_6. As outlined in the problem identification (Section 1.1), viable alternatives must demonstrate equivalent functionality, safety, reliability, economic potential, as well as environmental superiority (Uchii et al., 2023). In this study, these key elements are referred to as requirements. However, since these requirements lack specific, measurable parameters, it is necessary to establish quantifiable criteria to assess whether the alternatives meet the requirements. Section 4.1 presents the process how the criteria are derived from the requirements. Section 4.2 presents a selection of the key criteria considered for the evaluation process, followed by a more detailed elaboration. This process aims to address the following sub-question, which is answered in Section 4.3:

SQ2: What are the key criteria to consider when evaluating the viability of alternatives to SF_6 for use in gas-insulated switchgear?

4.1 Criteria derived from requirements

To quantify the five requirements, relevant articles were sourced from Scopus. This literature selection process is detailed in Figure A1 in Appendix A, and the articles are listed in Table A2. Initial research started with these articles, and their bibliographies were further explored to identify studies discussing the five requirements. Six studies, detailed in Table 4.1, provided measurable criteria based on the requirements. As a result of this literature review, 13 criteria were identified to which the alternatives must comply. These criteria are categorized per requirement and are presented in Table 4.1.

To provide equivalent functionality, the alternative technology should be able to interrupt the current flowing through the installation. This is one of the main qualities of SF_6 and is called dielectric strength, which is often measured relative to SF_6. In addition, the alternative gas should be kept in a gaseous state without a possibility to liquify, which is dependent on the boiling point of the gas. When the circuit is interrupted, the electrical arc resolves quickly, which can lead to damage to the installation. The arc-quenching capability of a gas defines if a gas can resolve the arc without leading to damages. At high voltage levels, temperatures can rise quickly which could lead to overheating of the installation. Therefore, the alternative gas needs to quickly resolve heat, which is referred to as heat dissipation.

In terms of safety, two main criteria were mentioned in all the articles. The alternative needs to be low enough in toxicity and non-flammable to ensure safe handling of the installation.

With respect to reliability, the alternative must be chemically stable over time to maintain its original chemical composition. The gases are operating under high pressure and heat in the electrical switchgear, which could affect the chemical stability. During operation the alternative should act without contributing to corrosion or other adverse effects to the switchgear.

Concerning the economic potential, the dielectric medium must be available on the market, preferably with multiple suppliers. The number of suppliers can be dependent on the presence of natural resources as well as regulatory restrictions. In addition, authors mentioned the economic feasibility of the alternative, which can be dependent on market availability or demand in other applications.

Regarding environmental superiority, the alternative should have no ozone depletion potential to comply with the Montreal Protocol and protect the ozone layer. The other criteria, and the core reason for the exploration of alternatives is the reduction of greenhouse gas emissions, and therefore the GWP of the alternative should be within the specified limits of Regulation (EU) 2024/573.

Table 4.1 Criteria definition for each requirement. Based on the following articles: 1. (Preve et al., 2015) 2. (Seeger et al., 2017a) 3. (Seeger et al., 2017b) 4. (Ullah et al., 2018) 5. (Owens et al. 2021) 6. (Franck et al., 2020)

Requirements	Criteria	Mentioned in articles					
		1	*2*	*3*	*4*	*5*	*6*
Equivalent functionality	Gaseous state / Boiling point		*X*	*X*		*X*	*X*
	Dielectric strength	*X*	*X*	*X*	*X*	*X*	*X*
	Arc-quenching capability		*X*	*X*			*X*
	High heat dissipation		*X*	*X*			*X*
Safety	Toxicity levels LC_{50}	*X*	*X*	*X*	*X*	*X*	*X*
	Flammability	*X*	*X*	*X*	*X*	*X*	*X*
Reliability	Non-corrosive	*X*				*X*	
	Chemical stability			*X*	*X*	*X*	*X*
Economic potential	Availability on market			*X*			
	Economic feasibility				*X*		*X*
Environmental superiority	Global Warming Potential (GWP)	*X*	*X*	*X*	*X*	*X*	*X*
	Ozone Depletion Potential (ODP)	*X*	*X*	*X*	*X*	*X*	*X*

4.2 Criteria selection

For the evaluation process, a selection of the criteria is made based on the frequency that the criteria were mentioned in the articles complemented with insights from the GIS specialist at TenneT. The criteria dielectric strength, toxicity, flammability, global warming potential, and ozone depletion potential were mentioned in all the reviewed articles and are therefore chosen for the evaluation process. The GIS specialist supplemented the list with the necessity for the alternative to stay in a gaseous state. The selected criteria are explained in more detail below.

4.2.1 Gaseous State

To ensure equivalent functionality compared to SF_6, it is important to maintain the insulating material in a gaseous state. The installations are designed to operate in a gaseous state, losing its functionalities in case the gas condensates. To assess whether a gas is suitable for use in a GIS, the boiling point is evaluated in degrees Celsius (ºC). The applicability is dependent on the outside temperature and is therefore not the same in every country. In most literature a reference temperature of below -30 ºC is considered. According to participant II, a value of -20 ºC is also sufficient in the Netherlands.

When a gas has a boiling point > -20 ºC, mixing the gas with a buffer gas like N_2 or CO_2, with boiling temperatures of −196 ◦C and −79 ◦C respectively, reduces the overall boiling point. In this way, an optimum can be found where the mixture reaches a boiling point of -20 ºC.

4.2.2 Dielectric strength

Dielectric strength is the indicator that determines the isolating capabilities of a gas. In the electrical switchgear, the operating gas must withstand a certain voltage level. All gases have a maximum voltage where it can no longer withstand the electrical flow, which is called electrical breakdown (Campo, 2008). At normal pressure conditions, the voltage breakdown (V_b) of SF_6 is 0.89 kV per meter (Koch, 2003). To compare the dielectric breakdown performance of various gases, SF_6 is considered equal to 1.00 and alternative gases are compared to SF_6 at atmospheric pressure. The electrical breakdown of air is about 0.3 kV per meter and therefore the dielectric strength is 0.37 – 0.40 compared to SF_6 (Ullah et al., 2020). According to participant II, a minimum dielectric strength of 0.8 is required relative to SF_6. In high voltage installations, the gas needs to withstand higher voltages, and possessing higher dielectric strength is beneficial. The dielectric strength is also dependent on the pressure. The formula for calculating voltage breakdown, as outlined by Husain & Nema (1982) is provided below.

$$V_b = \frac{B * p * d}{\ln(A * p * d) - \ln\left(\frac{1}{\gamma_e}\right)} \quad [6]$$

Here, the values B, A and γ_e are gas specific. For air, these values are 2737.5, 112.5 and 0.02 respectively. Resulting in the Paschen curve as shown in Figure 4.2.2. As can be seen, the dielectric strength increases with pressure. Higher operating pressures require GIS installations to be mechanically reinforced, necessitating the use thicker sealings to prevent leakages. According to participant II, current GIS equipment using SF_6 as an insulating medium operate at 5 to 8 bar and air would obtain the same dielectric strength in the range of 12 to 15 bar. Although this is technically possible, major implementation has not been achieved for high voltage switchgear. As showed in Figure 4.2.2, the voltage breakdown also increases with lower pressures. This is the case for vacuum circuit breakers. Here, the pressure is lowered to minimize ionization, which is the release of an electron and leads to an electric arc, resulting in voltage breakdown.

For gas mixtures, the dielectric strength can not be solely calculated from its components because it depends on the electron molecule interactions in the mixture (Franck et al., 2020). When the dielectric strength is higher compared to the average dielectric strength of the gases in the mixture, it is called a synergy effect. It is even possible that the dielectric strength of a gas mixture exceeds the highest dielectric strength of the gas with the highest value, which is referred to as a positive synergy effect.

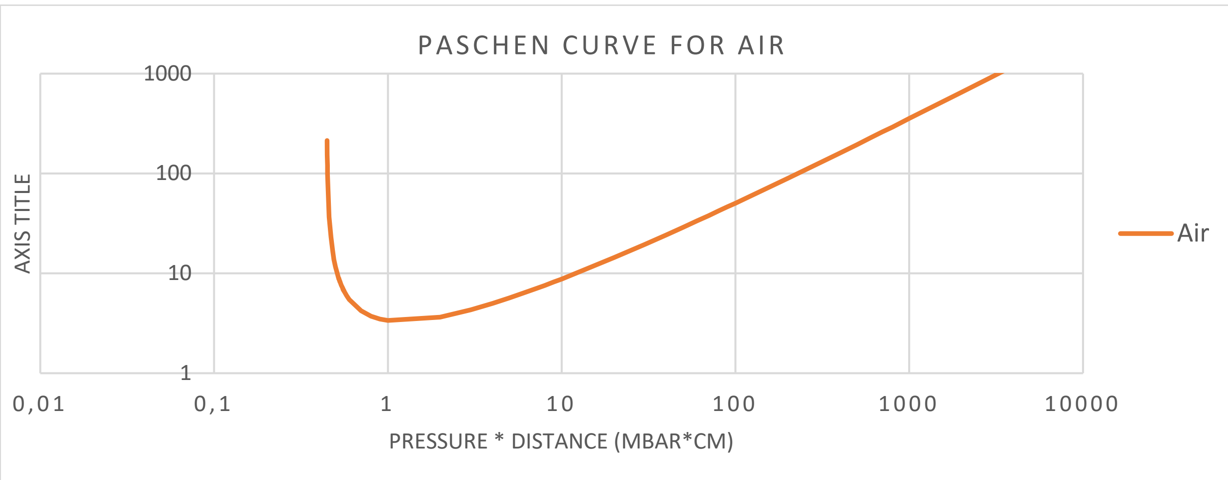

*Figure 4.2.2: Paschen curve for air, showing higher breakdown voltages for increased pressure on the right side (pressure * distance > 10) and vacuum on the left side (0.1< pressure *distance <1)*

4.2.3 Toxicity

To ensure the safe handling and operation of the electrical switchgear, the gas should be low enough in toxicity levels. In this research, the toxicity of gases is determined using the standard metric known as the Lethal Concentration 50 (LC_{50}). The LC_{50} indicates the concentration of a gas in the air in parts per million (ppm) that is lethal to 50% of the test population within a specified exposure time. This measurement is widely used in toxicology of gases and provides a benchmark for six health risk levels. In most literature regarding gas toxicity, rats are commonly used as test animals with an exposure time of four hours. To ensure consistency, outcomes of studies with this approach are compared. When the LC_{50} values are not available, non-numerical values are chosen. As presented in Table 4.2.3, the degree of toxicity is measured by a toxicity rating according to the Hodge and Sterner scale (Konan et al., 2022).

Table 4.2.3: Lethal Concentration 50 toxicity (LC50) classes on the Hodge and Sterner Scale (Konan et al., 2022).

Toxicity rating	Commonly used term	LC_{50}: Exposure of rats for 4 hours [ppm]
1	Extremely toxic	10 or less
2	Highly toxic	10-100
3	Moderately toxic	100-1000
4	Slightly toxic	1000-10.000
5	Practically non-toxic	10.000-100.000
6	Relatively harmless	> 100.000

4.2.4 Flammability

When a gas is used as insulating medium in electrical switchgear, it is important to ensure that the gas is not flammable or explosive when operational. This is especially crucial when the gas contains oxygen atoms, as this can increase the risk of explosions or fire (Preve et al., 2015). For gas mixtures, the non-flammability should be checked at different temperatures because the temperature can change with gas pressure. To define the flammability of a gas, an internal arc fault test is performed to see how much energy is released during faults, and how the gas mixture reacts to this energy (Preve et al., 2015).

4.2.5 Global Warming Potential

The Global Warming Potential (GWP) was introduced for policymakers to measure the global warming effect of each greenhouse gas relative to CO_2 (Intergovernmental Panel on Climate Change, 1990). The GWP helps policymakers to implement regulations reducing the most harmful greenhouse gases. One factor for the definition of GWP is the considered atmospheric lifetime, as not all gases stay in the atmosphere for the same time. CO_2 for example is removed through carbon cycles, where SF_6 stays in the atmosphere for about 1278 years, due to its chemical stability. In the assessment reports of the IPCC, three different timescales for the calculation of GWP are defined, consisting of 20, 100 and 500 years. As stated in the physical science basis of assessment report 5 (Intergovernmental Panel on Climate Change, 2013a), the confidence of the timescale for 500 years is very low because of nonlinear effects, and metric values are therefore no longer provided in the IPCC reports since the 5th assessment report. The timescale of 100 years provides higher levels of certainty and is therefore generally accepted. For this reason, the timescale considered in this research is 100 years. The formula for calculating the GWP over a 100 year timeframe, as outlined in Chapter 8 of the supplementary material from the IPCC's fifth assessment report, is provided below (Myhre, 2013).

$$GWP_{100} = \frac{\int_0^{100} RF_{gas}\,(t)\,dt}{\int_0^{100} RF_{CO2}\,(t)\,dt} \quad [1]$$

Here, RF_{gas} (t) is the radiative forcing of the reference gas over period t. To calculate GWP_{100} this value is compared to the radiative forcing of CO_2 over the period of 100 years. The radiative forcing is gas specific and is dependent on the ability of a molecule to absorb radiation. When sunlight reaches the Earth, it is absorbed in converted into heat. This heat is in then partly emitted back into the atmosphere as infrared energy. The greenhouse gases in the atmosphere absorb some of this energy, and re-emit it in all directions. This process is called the radiative forcing, which contributes to the warming of the atmosphere.

To reduce the Global Warming Potential of gases such as SF_6, creating a mixture with multiple gases is a viable option. The total GWP can be evaluated based on the mole- and mass fractions of each gas. The GWP of a gas mixture can be calculated using the formula as presented by (GE Vernova & Hitachi Energy, 2023):

$$GWP_{mixture} = \sum \%_{wt\,i} * GWP_i = \sum \frac{\%_{mol_i} * M_i}{\sum_k \%_{mol_k} * M_k} * GWP_i \quad [2]$$

The mole fractions of each gas are presented as $\%_{mol_i}$ and the molecular weight of each gas as M_i, and the gas specific global warming potential as GWP_i. The total weighted molecular weight of the mixture is presented in the denominator. For example, the following mixture is designed to reduce the GWP impact of SF_6 by incorporating O_2 and CO_2. The molecular weights of SF_6, O_2, and CO_2 are 146.06 g/mol, 32.00 g/mol, and 44.01 g/mol, respectively. When a mixture with mole fractions of 10% SF_6, 5% O_2, and 85% CO_2 is considered, the following GWP value for the mixture applies.

$$GWP_{mixture} = \frac{0.10 * 146.06 * 24300 + 0.05 * 32.0 * 0.0 + 0.85 * 44.01 * 1.0}{0.10 * 146.06 + 0.05 * 32.0 + 0.85 * 44.01} = 6621 \quad [3]$$

The GWP of this mixture is reduced by 73% compared to pure SF_6. Reducing the GWP is beneficial to adhere to a GWP limit of 1000 as proposed in Regulation (EU) 2024/573. altering the gas composition effects other criteria as well. Typical mixture gases are N_2, O_2, and CO_2, which have lower boiling points and lower dielectric strength compared to SF_6. For the mixture presented in Formula 3, both the boiling point and the dielectric strength decrease. A lower boiling point is advantageous, allowing the mixture to remain gaseous in colder climates. However, the reduction in dielectric strength could negatively impact the mixture's technical functionality.

4.2.6 Ozone Depletion Potential

In 1974, Frank Sherwood Rowland and his post-doctoral student Mario J. Molina published an article to raise awareness for the threat of chlorofluorocarbons (CFCs) to the ozone layer (Molina & Rowland, 1974). The human made CFCs were chemically inert and able to reach the stratosphere. Here, the molecules separate into chlorine atoms under ultra-violet light, contributing to the depletion of the ozone layer. The Montreal Protocol, an international treaty adopted in 1987, was introduced to phase out the use of ozone depleting substances. At that time, trichlorofluoromethane (CFC-11) was widely commercialized and used as a refrigerant. Therefore, CFC-11 was taken as the reference to compare different gases, leading to the following formula, which is considered to evaluate the alternatives.

$$ODP_{gas} = \frac{impact\ of\ gas\ on\ ozone\ layer}{impact\ of\ CFC11\ on\ ozone\ layer} \quad [5]$$

4.3 Answer to sub-question 2

This chapter was dedicated to establishing a set of quantifiable criteria necessary for assessing potential SF_6 alternatives. For an alternative to be considered viable, it must fulfil to the requirements as outlined by Uchii et al. (2023). Given that these requirements are qualitative and lack measurable parameters, it was necessary to translate them to quantifiable criteria that could be applied to evaluate whether the alternatives meet the defined requirements.

Addressing sub-question 2: “What are the key criteria to consider when evaluating the viability of alternatives to SF6 for use in gas-insulated switchgear?” the study identified a set of 12 criteria which include boiling point, dielectric strength, arc-quenching capability, high heat dissipation, toxicity levels (LC50), flammability, non-corrosiveness, chemical stability, market availability, economic feasibility, GWP, and ODP. Out of these, six were prioritized as key criteria crucial for assessing the viability of alternatives. These are dielectric strength, toxicity (LC50), flammability, GWP, boiling point, and ODP. These criteria collectively ensure that the requirements are met for a SF_6 alternative.

5. Multi-criteria evaluation

This chapter aims to evaluate the possible alternatives in electrical switchgear. The alternatives are categorized based on their chemical composition and are described in section 5.1. Subsequently, the specific gases of each categorized molecule group are discussed. After the evaluation of alternatives, the most suitable alternatives are discussed in section 5.2, answering the third sub-question:

SQ3: What are the alternatives to SF_6 and how do they perform when evaluated against the defined criteria?

5.1 Defining the alternatives

According to Düzkaya et al. (2020), the alternative dielectric gases for gas insulated switchgear can be classified under the titles of non-synthetics, hydrocarbons (HCs), fluorocarbons (FCs), hydrofluorocarbons (HFCs), fluoronitriles (FNs), fluoroketones (FKs), chlorocarbons, bromocarbons and iodide-carbons. Vacuum interrupters and Hydrofluoroolefins were two technologies mentioned by Billen et al. (2020) and Berroual and Haddid (2017) as possible SF_6 substitutes. The alternatives are further elaborated on in the following sections. The single gases are evaluated using the criteria and are presented in appendix C, table C.1. Some gases were mixed to optimize performance, these mixtures are presented in appendix C, table C.2.

Non-synthetic gases are referred to as stable molecules that occur in the atmosphere. The molecules considered for application in electrical switchgear are N_2, O_2, and CO_2. The advantages of non-synthetics are the lower GWP values, costs, boiling temperatures, and non-toxicity. However, the dielectric strength of non-synthetics is significantly lower compared to SF_6 (Düzkaya et al., 2020). The exact dielectric strength is in the range of 0.3 to 0.43, for which the pressure must be increased by a factor of 2.5 to 3 to meet the performance of SF_6. According to Uchii et al. (2023) and GE Vernova and Hitachi Energy (2023), CO_2 is much better than N_2 in terms of switching performance, thus, CO_2 should be the best candidate of the main gas of mixtures. An optimal gas mixture of 70% CO_2 and 30% O_2 represents the most ideal mixture for achieving maximum dielectric strength when only non-synthetic gases are considered (Uchii et al., 2023). The application of only non-synthetic gases is theoretically possible, but constructing an installation that can withstand such high pressures is difficult in practice.

Fluorocarbons (FCs) are considered as a highly stable molecule due to the strong carbon-fluorine bond. The molecules that are considered in this research are CF_4, C_2F_6, C_3F_8, C_4F_8 and c-C_4F_8. For larger molecules, with more carbon and fluorine atoms, the dielectric strength and stability increases (Düzkaya et al., 2020). The molecules are non-toxic, except for CF4, which toxicity is defined being low (Beroual, 2017). The global warming potential for the molecules is in the range of 6500 to 8700, significantly above the 1000 limit. The molecules C_4F_8 and c-C_4F_8 have a boiling point of -6 ^oC and -8 ^oC respectively, making them unsuitable for application.

Hydrofluorocarbons (HFCs) consist of hydrogen, fluorine, and carbon atoms. The molecules that are mentioned in academic literature to represent a possible alternative to SF_6 are CHF_3 and $C_2H_2F_4$. Just like fluorocarbons, hydrofluorocarbons show higher dielectric strength and stability with larger molecules. The molecules are quite different, as CHF_3 is unsuitable with a GWP of 14800 and a dielectric strength of 0.29. The molecule $C_2H_2F_4$ is a potential substitute for SF6, as it has a dielectric strength of 0.85, is nontoxic, and has a boiling point of -26 ^oC. The downside of $C_2H_2F_4$ is the GWP of

1300. As presented in table C2, mixtures with N2 and air are proposed, but the GWP of the mixtures is not below 1000. In addition, HFCs are listed in the Kyoto Protocol (1998) as fluorinated greenhouse gases, leading to restrictions on their use, which are further reinforced by Regulation (EU) 2024/573, limiting the HFC market and stating a total phase-out by 2050.

Hydrofluoroolefins (HFOs) are characterized by carbon-carbon double bonds and fluorine and hydrogen atoms. In this study five molecules are investigated, which are almost identical in atom composition. All molecules have low GWP values in the range of 1 to 18. The molecule $C_3H_2F_4$ with the name R1234ze (E) is the most promising molecule, being non-toxic, having a GWP of 6, a dielectric strength of 0.7 and a boiling point of -19 ºC. The disadvantage of HFOs is that they can decompose during electrical discharges, leading to the formation of carbon dust deposits on insulators, which can compromise system integrity. Due to this risk, particularly in high-voltage applications, HFOs are not widely considered suitable replacements for SF_6 (Beroual et al., 2017).

Fluoronitriles (FNs) consist of fluoride, carbon, and nitrogen atoms. This study focusses on CF_3CN, C_2F_5CN, C_3F_7N, and C_4F_7N. Except for C_4F_7N, fluoronitriles are acute toxic to humans and precautions are obliged for its use (Düzkaya et al., 2020). C_4F_7N shows multiple advantages as being non-flammable and having a dielectric strength in the range of 2.0 to 2.2. The downside of C_4F_7N is the GWP of 2750 and a boiling point of -4.7 ºC, making application of the pure molecule not possible. However, the high dielectric strength makes it possible to find a suitable mixture. Mixtures ratios proposed in literature studies are presented in table C2. Suitable mixture ratios with GWP values below 1000, boiling points below -25 and dielectric strength above 0.8 can be derived using small amounts of C_4F_7N. The best ratios are further discussed in section 5.2.

Fluoroketones (FKs) show multiple similarities to fluoronitriles, but the nitrogen atom is substituted by an oxygen atom. Among the Fluoroketones C_4F_8O, $C_5F_{10}O$, and $C_6F_{12}O$ are discussed the most in academic literature for electrical applications. $C_4F_8O_2$, being the smallest molecule, is unsuitable because of its GWP of 13900. The other two molecules show practically non-toxic levels, are not flammable and have a GWP below 1. Their dielectric strength is in the range of 1.7 to 2.8 making them highly suitable for implementation. However, the main disadvantage of the two molecules is the high boiling points of 27.0ºC and 49.2ºC for $C_5F_{10}O$ and $C_6F_{12}O$ respectively. As pure implementation is not possible, the gases need to be used with other buffer gases with lower liquefaction temperatures. Possible mixtures are presented in table C2 but achieving boiling points below -25ºC with a dielectric strength above 0.80 seems to be impossible.

Hydrocarbons (HCs) are formed by a combination of hydrogen and carbon atoms. The most common used hydrocarbons for dielectric application are CH_4 and C_2H_6. The hydrocarbons show multiple advantages with a GWP between 10 and 25, being non-toxic, and boiling points below -30ºC. The downside of HCs is that they are highly flammable (Unacademy, 2022), and CH_4 is one of the six greenhouse gases of which the emissions must be reduced according to the Kyoto Protocol.

Chlorocarbons consist of chloride and carbon atoms. The molecules that are referred most for electrical applications are CF_2Cl_2 and CF_3CHCl_2 because their fluorine atoms increase the dielectric strength of 0.9 and 1.3 respectively. The molecules are considered practically non-toxic and non-flammable. According to Juliandhy et al (2017), the molecule CF_3CHCl_2 shows the most potential as alternative in switching designs. However, this molecule has a boiling point of 28ºC and a dielectric strength of 1.3 is not high enough to consider mixtures.

Bromocarbons are characterized by bromine and carbon atoms. For electric appliances, CH_3Br and CF_3Br are the most studied molecules. CH3Br has a low dielectric strength of 0.29, making the molecule unsuitable for application. CF_3Br is non-flammable, and has a boiling point of -58ºC. The downside of this molecule is the low boiling point of 0.54 and the GWP of 5800.

Iodide-carbons consist of iodine and carbon atoms. The most common used iodide-carbons for dielectric application are CF_3I and CH_3I, with suitable dielectric strength of 1.3 and 1.2 respectively. The GWP for both molecules is below 5. CH_3I has a boiling point of 42.5ºC, making its use unsuitable. The boiling point of CF_3I is -22.5ºC, but the molecule is potentially mutagenic.

Vacuum switchgear does not involve a gas in the circuit breaker, and therefore the flammability, toxicity, boiling point, and GWP does not apply. Typical vacuum levels inside the device are about 10^{-4} Pa ($\sim 10^{-6}$ mbar) (Slade, 2020). For a vacuum switchgear, the pressure is kept very low to ensure there are no free electrons to establish an arc. The formation of an arc is prevented, and the circuit breaker stops the current flowing through the installation. Only the circuit breaker is kept vacuum and the other parts of the switchgear are insulated by the use of a gas, which were mostly SF6. Since 2010, switchgear insulated with gases of natural origin has been installed. Additionally, SF6-free switchgear designed for voltage levels of 145 and 170kV has been developed and recently put into operation (Smeets et al., 2022).

Group	Gas	Exclude GWP > 1000	Exclude boiling point	Exclude toxicity	Exclude flammability	Exclude ODP	Dielectric strength > 0.8	Included
Sulfur Hexafluoride	SF6	22.800	-64	100.000	Non-flam.	Zero	1.0	SF6
Non-synthetics	CO2	1	- 79	300.000	Non-flam.	Zero	0.3 - 0.5	CO2
	N2	0	- 196	non-toxic	Non-flam.	Zero	0.34 - 0.44	N2
	Clean air	< 1	- 193	non-toxic	Non-flam.	Zero	0.37 - 0.40	Clean air
	CO2 / O2	< 1	< -79	non-toxic	Non-flam.	Zero	0.45	CO2 / O2
Fluorocarbons	CF4	6500						
	C2F6	9200						
	C3F8	7000						
	C4F8	8700						
	c-C4F8	8700						
Hydrocarbons HC	CH4	25	- 161	57.000	Highly-flam.			
	C2H6	10	- 84	80.000	Highly-flam.			
Hydrofluorocarbons HFC	CHF3	14.800						
	C2H2F4 (R134)	1300	- 26	567.000	Non-flam.	Zero	0.85	C2H2F4
	C2H2F4 + N2	1214	< - 26	non-toxic	Non-flam.	Zero	0.85 - 0.90	C2H2F4 + N2
	C2H2F4 + clean air	1159	< - 26	non-toxic	Non-flam.	Zero	0.85 - 0.90	C2H2F4 + clean air
Hydrofluoroolefins HFO	R1336mzz (E)	18	7.5					
	R1336mzz (Z)	2	33.4					
	R1234yf	1	- 29.5	400.000	Mildly-flam.			
	R1234ze (E)	6	- 19	207.000	Non-flam.	Zero	0.76	R1234ze (E)
	R1234ze (Z)	< 10	9.6					
Hydrochlorofluoroolefins HCFO	HCFO1233zd	7	18.3					
Fluoroethers HFE	HFE245cb2	697	5.6					
Fluoronitriles FN	CF3CN	1030	- 62	Highly				
	C2F5CN	1800	- 32	Highly				
	C3F7N	2100	- 2					
	Pure C4F7N	2750	- 4.7					
	C4F7N + CO2 + O2	301-614	-30 to -25	12.000	Non-flam.	Zero	0.8 - 1.0	C4F7N + CO2 + O2
	C4F7N + N2	1334	-25 to -20	non-toxic	Non-flam.	Zero	0.8 - 1.0	C4F7N + N2
	C4F7N + CO2	1104	-25 to -10	120.000	Non-flam.	Zero	0.8 - 1.0	C4F7N + CO2
Fluoroketones FK	C4F8O	13.900						
	Pure C5F10O	< 1	27					
	C5F10O + clean air	< 1	0					
	C5F10O + CO2 + O2	< 1	- 5					
	C6F12O	< 1	49.2					
Fluorooxiranes	C4F8O	4100						
Chlorocarbons	CF2Cl2	10200						
	CF3CHCl2	23	28					
Bromocarbons	CH3Br	5	3.4					
	CF3Br	5.800						
Iodide-Carbons	c-ClF3	14.4000						
	CF3I	< 1	- 22.5	Mutagenic				
	CH3I	< 1	42.5					
Vacuum	No gas	< 1	none	non-toxic	Non-flam.	Zero	None	Vacuum

Figure 5.1: Overview of SF_6 alternatives with selection on identified criteria.

5.2 Assessment of the most suitable alternatives

This section aims to evaluate the possible alternatives to SF_6 for the use in electrical switchgear evaluated against the criteria as identified in chapter 4. The promising molecule groups as identified in section 5.1 was further explained by single molecules and promising mixtures. A visual presentation of all the possible alternative is shown in Figure 5.1. The molecule groups are presented in the left column after which the specific gases are listed on the right, followed by the criteria, which are all equally weighted. When a criteria is met, the value is outlined in green. When the criteria are close to the reference, it is outlined in orange, as slight alternations with mixtures or pressure levels could improve the outcome. If the criteria are not met, they are outlined in red, which means they are not suitable for implementation. In the column on the right, the alternatives that meet all the criteria are presented in green and the alternatives that are close to meeting all criteria are presented in orange.

The most promising alternatives are the non-synthetic gases, $C_2H_2F_4$ and its mixtures, R1234ze (E), the mixtures of C_4F_7N and vacuum. The non-synthetic gases show high potential in terms of GWP, providing options in the range of 0 to 1. The downside of non-synthetic gases is their low dielectric strength and if the same performance to SF6 has to be reached within the same volume, the pressure has to multiply by a factor of 2,5 to 3, resulting in an operating pressure of 12 to 15 bar which is theoretically possible but hard to realize. In terms of switching performance, CO_2 performs better compared to N_2, making it the best option to be used for interruption. According to Uchii et al. (2023), when solely non-synthetic gases are used for interruption, a mixture with a concentration of 30% O_2 and 70% CO_2 is preferred, because of the positive synergy effect as presented in Figure C.2 in Appendix C. The addition of O_2 to the mixture increases the dielectric strength while also reducing toxicity. The biggest challenge for the use of non-synthetics as interrupter is achieving a similar equipment size to SF_6 interrupters. According to Uchii et al. (2023), this could be manageable by innovations and design improvements, such as special dielectric coatings, novel gas interrupter concepts and elevated filling pressure.

$C_2H_2F_4$ shows great potential, meeting all the criteria except for GWP. Pure $C_2H_2F_4$ has a GWP of 1300, which can be decreased by mixing the gas. According to Ullah et al. (2018) the highest synergetic effects are shown for the mixtures $C_2H_2F_4$/air having the mixing ratio of (70/30%) and $C_2H_2F_4/N_2$ with the mixing ratio of (80/20%). These mixtures lower the GWP, but the values for the $C_2H_2F_4/N_2$ and $C_2H_2F_4$/air mixtures result in a GWP of 1214 and 1159 respectively, following the formula as presented in section 4.1. The GWP of both gases is accomplished where a mixture ratio < 48% consist of $C_2H_2F_4$ and > 52% consist of the buffer gas. In the research performed by Ullah et al. (2018), mixture ratios for 50%/50% were evaluated and it was found that the dielectric strength of both mixtures was below pure $C_2H_2F_4$. For the $C_2H_2F_4$/air mixture, the maximum voltage breakdown decreased by 17% leading to a dielectric strength of 0,67 relative to SF_6. The $C_2H_2F_4/ N_2$ mixture shows better potential with only a 6% decrease, which leads to a dielectric strength of 0,75 compared to SF_6. This could possibly be overcome with higher pressures, but the GWP value is still close to 1000. When the GWP of $C_2H_2F_4$ was underestimated and gets adjusted >1300 in the following IPCC report, the gas is no longer allowed for application. With several gases being adjusted in earlier published Assessment Reports by the IPCC, this represents an excessive risk for developers.

Another alternative gas with high potential is R1234ze (E), with the molecule structure $C_3H_2F_4$. This HFO was introduced as a sustainable alternative to SF_6. The gas is relatively recently introduced, being first mentioned in 2010 in the Scopus database. The gas nearly meets all the criteria, with a boiling point of -19 ºC and a dielectric strength of 0,76. However, when the gas is applied as an interruption gas, the gas degrades after the first interruption, creating fine dust that deposits on the electrodes (Soulie, 2022).

This dust negatively effects the insulation properties of the gas. According to Soulie (2022), the gas can be used as an insulation gas, but not as an interrupting gas as it gets degraded by arcs. This was also confirmed by Smeets et al. (2022), mentioning that the gas can only be used for insulation and not for switching.

Pure C_4F_7N is not suitable for application because of its high GWP value of 2750 (IPCC, 2021). However, the high dielectric strength of C_4F_7N (2,0) makes it suitable for mixtures. As explained earlier, CO_2 is the most applied mixture gas, as it provides the highest arc quenching capabilities among the non-synthetic gases. For a mixture at equal pressure, the dielectric strength is 1,0 for a concentration of C_4F_7N in the range of 18 to 20% (Kieffel 2014). A concentration of 18 to 20% would exceed the GWP limit of 1000 as shown in Figure 5.2. According to GE Vernova & Hitachi Energy (2023), O_2 can be added to the C_4F_7N /CO_2 mixture to reduce the content of toxic by-product CO, and it also has a positive effect on the switching performance. In the literature, two mixture ratios were found for (C_4F_7N / O_2 / CO_2), with mixture ratios of (6% / 5% / 89%) and (3.5% / 13% / 83.5%). In both cases, the mixture consists mostly of CO_2. The first mentioned mixture ratio shows advantages in terms of dielectric strength (0,96), while having a boiling temperature of -25 ºC and a GWP of 614. The second mixture is advantageous in colder climates with a boiling temperature of -30 ºC and has a GWP of 394, while the dielectric strength (0,87) is slightly lower. Both gas mixtures are suitable for application, depending on constructor preferences.

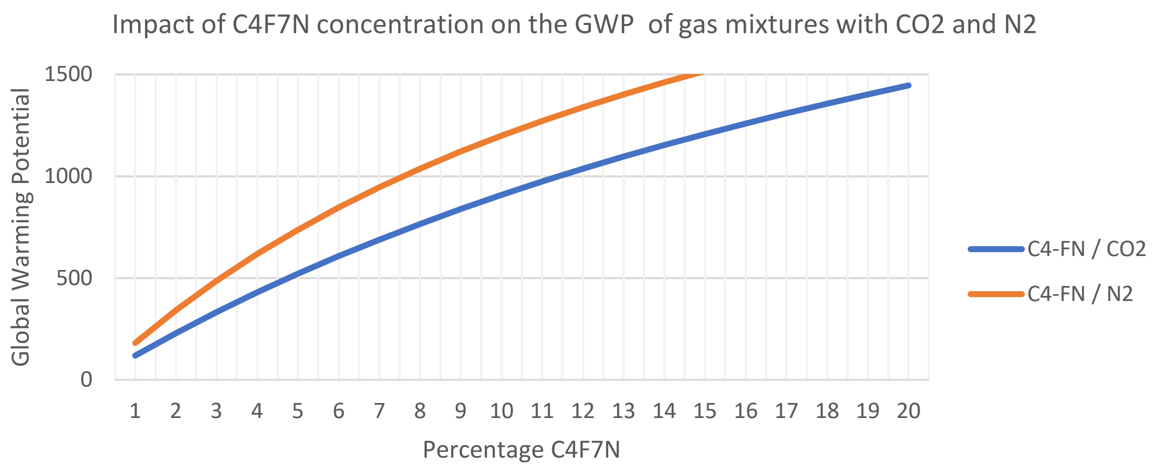

Figure 5.2: Demonstration that GWP surpasses the limit of 1000 for C_4F_7N concentrations exceeding 11% for CO_2 mixtures and 7% for N_2 mixtures.

The second suitable alternative is interruption through vacuum. As there is no gas involved, there is no GWP, no ODP, no toxicity, no boiling point, and it emits no flame or smoke. Vacuum interruption is widely used in low and medium voltage levels as the technology shows major advancements in GWP over SF_6. However, the application in high voltage is more difficult, as the insulating capacity of vacuum is not directly proportional to the size of the insulating gap (Kieffel et al., 2015). There is a saturation point, making it hard to establish breakdown at high voltages. According to Kieffel et al. (2015), the application of vacuum interrupters above 145kV is limited and not considered economically viable.

5.3 Answer to sub-question 3

This chapter aimed to explore various potential alternatives to SF_6, assessing their performance relative to the established criteria. Specifically, the alternatives that showed the best performance were a combination of O_2 and CO_2, vacuum interrupter technology, and a mixture of C_4F_7N with CO_2 and O_2. Each of these alternatives demonstrated promising performance in alignment with the defined criteria. Notably, the combination of O_2 and CO_2, as well as the vacuum interrupter, are advantageous due to their low GWP of below 1. On the other hand, the C_4F_7N mixture offers benefits with its moderate GWP between 1 and 1000, providing a viable option during the transitional phase.

6. Prospective analysis

This chapter aims to evaluate the three most suitable alternatives as discussed in chapter 5 and determine the effects for implementation. The drivers and challenges affecting the alternatives are discussed in section 6.1. In section 6.2, the impact of the drivers and challenges is discussed for future generation platforms. To acquire understanding in future trends, an interview is conducted with the project developer of the TenneT innovation track, who is researching innovations for future generation offshore platforms. The participant is referred to in this study as participant III. To obtain insights from a constructor perspective, an interview is conducted with the sustainability program leader of General Electric. The participant is referred to in this study as participant IV. This interview highlighted environmental concerns associated with the construction of various switchgear technologies. This will be discussed in more detail in section 6.4. The following sub-question is being addressed in this chapter:

SQ4: What are the key drivers and challenges, and how do they influence the adoption of SF_6 alternatives in the offshore wind sector?

6.1 Drivers and challenges

The most suitable alternatives have different characteristics, which pose advantages and challenges for their implementation. The C_4F_7N mixture faces regulatory challenges as its GWP is disadvantageous compared to the other alternatives. The vacuum interrupting technique faces challenges in terms of meeting high voltage capacities. The O_2/CO_2 mixture is limited by its dielectric strength, leading to an increased installation footprint. The adoption of switchgear is dependent on future converter station adaptations. Resulting from the challenges, there are three questions which effect the choice of implementation. First, what is the required capacity for electrical switchgear on future generation platforms. This is important because the vacuum technology is not easily scalable to voltage levels above 170 kV. Second, what is the space available for the electrical switchgear, and do the installations fit on the platform. This is of main importance for the vacuum and O_2/CO_2 installations, as their installation sizes are larger compared to the SF_6 and C_4F_7N insulated switchgear, for which the current platform is designed. The third question relates to the number of constructors providing an installation with a GWP below 1. This mainly impacts C_4F_7N, as this option is accepted through regulation (EU) 2024/573 when there is equal or less than 1 providers available. According to participant III, the main driver with regard to the electrical switchgear is increasing the offshore inter-array cables connected to the wind turbines to reduce the number of bays and switchgears.

6.2 Impact of drivers and challenges on future platforms

The offshore wind energy sector is rapidly expanding. The European Commission published a dedicated EU strategy on offshore renewable energy (COM/2020/741), stating that the offshore renewable energy capacity has to multiply by a factor of 30 by 2050. This capacity growth creates market opportunities and adaptations for future projects. To clarify the impact of the challenges, section 6.2.1. describes the expected design for the future platforms, aiming to answer the expected capacities and available space for larger installations. To provide clarity to the third uncertainty, section 6.2.2 describes the current advancements of various constructors and their progress regarding the construction of electrical switchgear with a GWP below 1.

6.2.1 Future generation platform

Currently, the contracting parties for the planned offshore converter stations as described in chapter 3 are allocated. These projects are commissioned between 2029 and 2032 and are defined by TenneT as the first-generation platforms. The electrical switchgear for these platforms was ordered before 11 March 2024, through which the GWP restrictions do not apply following the exemption as stated in paragraph 14 of Regulation (EU) 2024/573. In the Netherlands, General Electric and Hitachi opted to implement electrical switchgear with C_4F_7N as the insulation and interruption medium. In Germany, Siemens is installing the 8VN1 installation with clean air insulation and a vacuum circuit breaker. According to participant II, the decision for the type of electrical switchgear has been finalized and is considered fixed for these projects. Given the planned capacity upscale, it is therefore more relevant to examine the type of switchgear to be installed on future platforms.

According to participant III, one of the main drivers for innovation is lowering the amount of bays to reduce cost and climate impact. For the first-generation platforms, the cables used to connect the wind turbines to the offshore platform are 66kV transmission cables. However, the GIS installations can control 145kV, and a lot of its capacity is thus not used. For this reason, the innovation track of TenneT considers doubling the voltage capacity of the cable to 132kV. According to the power formula, the power transmitted through the cables can double if the voltage is increased by a factor of two, while keeping the current constant.

$$Power = Voltage * Current$$

In this way, more wind turbines can be grouped together, or the average capacity of wind turbines could increase. As stated by Wiser et al. (2021), the turbine capacities will exceed to 17MW. This was confirmed by participant III, mentioning that the second-generation platforms are being built between 2032 and 2037 with an expected turbine capacity from 15 up to 20MW. With each block still having a capacity of 500MW and higher power capacities per bay, the number of bays will decrease with 132kV transmission cables. The single-line diagram for the second-generation platform is presented in Figure 6.2.1. Similar to the first-generation design, this design will feature four identical blocks. In this block the seven wind turbine bays are reduced to four and the two transformer bays are combined in one bay. The auxiliary bay is removed and a possible bay for offshore consumers is added to each block. The offshore consumer is an external company using sustainable energy offshore, like an electrolyser to produce hydrogen, offshore batteries, or a CO_2 storage facility. The second-generation platform achieves a reduction of 4 bays per block, amounting to a total decrease of 16 bays. Consequently, the second-generation platform comprises 24 bays in total.

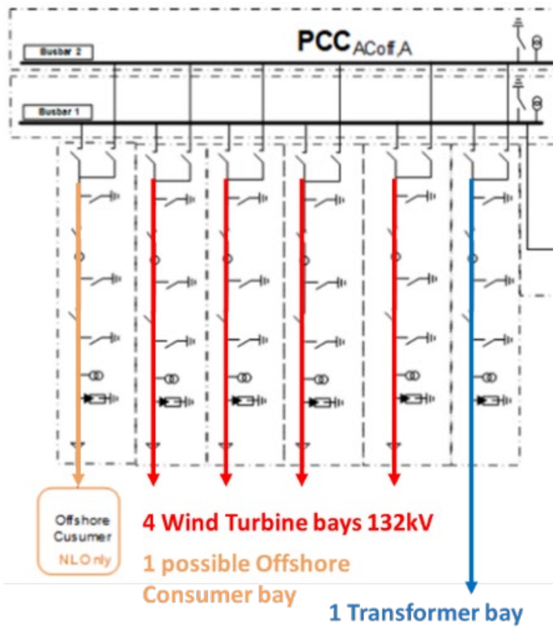

Figure 6.2.1. Switchgear installations on the second-generation offshore platform.

The vacuum and CO_2/O_2 installations are slightly larger, but as the total number of bays is reduced, their total surface decreases for next generation platforms. In the first-generation platform, there are two GIS rooms side by side, each measuring 12 meters in length and 35 meters in depth, resulting in a total GIS area of 840 m^2. According to the technical brochures listed in Table 3.4.3, the area for the Hitachi Econiq-04 is 4.8 m^2 per bay, and for the F35g of General Electric it is 2.96 m^2 per bay. With 40 bays, this leads to a total GIS surface of 192 m^2 for Hitachi and 118.4 m2 for General Electric. The vacuum switchgear by Siemens measuring 5.5 m^2 per bay, totals 132 m^2 for 24 bays in future generation platforms. This results in a surface reduction of 60 m^2 compared to the Hitachi design, yet it increases by 13.6 m^2 compared to the General Electric design from the first-generation platform. With slight alterations in a 840 m^2 room, there are no space constraints for vacuum switchgear in future generation platforms.

The offshore capacity targets as formulated by the European Commission are projected until 2050. According to participant III, the second-generation platforms are constructed between 2032 and 2037 and the third-generation platforms are planned for development between 2038 and 2050. The transmission cables will likely have a capacity of 132kV, as higher voltage levels would lead to extensive adjustments on the platform, which are not beneficial (participant III). The wind turbine capacities are expected to increase in the range of 20MW, which are still compatible with the same design. The third-generation platforms are expected to maintain a total capacity of 2GW, as increasing capacities would impose higher investment risks for the companies constructing the wind farms (participant II). Minor adjustments will therefore have to be made to the third-generation platforms, with a design being similar to the second-generation platform.

To answer the first two questions as raised in section 6.1, the capacity required for the electrical switchgear is unlikely to exceed 145 kV as the 132 kV cables are fit for larger turbine capacities. There will be some more space available in the GIS room as the number of switchgear installations is reduced from 40 to 24. These future advancements are both beneficial for the vacuum and CO_2/O_2 switchgear. Table 6.2.1 shows the platform generations with expected turbine and cable capacity with the matching switchgear capacity.

In the right column, the number of manufacturers is listed. For the first-generation platform, Siemens Energy, Hitachi Energy and General Electric are producing a 145kV SF6 electrical switchgear, which will continue to be available for the second and third generation. Hitachi Energy and General Electric are the constructors of the 145kV C_4F_7N switchgear types, which also have market availability for the second and third generation platforms. Currently, Siemens Energy is the only manufacturer of 145kV rated vacuum switchgear, indicated as N = 1. The potential manufacturers of high voltage vacuum switchgear will be discussed in the following section. Presently, there is no manufacturers of the CO2 / O2 technology, hence N = 0. The potential for new manufacturers in the second and third generation will also be explored in the following section.

Table 6.2.1: Future trends for offshore converter stations and expected number of manufacturers for each switchgear type (N = number of constructing companies of a 145kV electrical switchgear)

Year	Generation	Wind turbine capacity	Cable capacity	Switchgear capacity	SF6	C_4F_7N	Vacuum	CO_2 / O_2
2029 - 2032	First	≤ 15 MW	66 kV	145 kV	N ≥ 2	N ≥ 2	N = 1	N = 0
2033 - 2037	Second	15–20 MW	66-132 kV	145 kV	N ≥ 2	N ≥ 2	N ≥ 1	N ≥ 0
2038 - 2050	Third	≥ 20 MW	132 kV	145-170 kV	N ≥ 2	N ≥ 2	N ≥ 1	N ≥ 0

6.2.2 Constructors for vacuum, C_4F_7N, and CO_2/O_2 switchgear

As for now, the only three available contractors to deliver the electrical components for the platform are General Electric, Hitachi Energy, and Siemens Energy. Currently, Siemens is the only constructor that delivers a 145kV electrical switchgear with a GWP below 1, with their vacuum switchgear. Article 11 (b) of regulation (EU) 2024/573 states that a monopoly on switchgear installations may not be formed two years after the specified dates. If there are no companies entering the market with another switchgear type with a GWP below 1, Hitachi and General Electric are still allowed to put their C_4F_7N installations in operation until 2030 for switchgear up and including 145kV, and until 2034 for switchgear above 145kV, following a procurement procedure that considers the technical specificities of the equipment. When additional manufacturers to Siemens Energy providing switchgear below a GWP of 1, the C_4F_7N technology must be phased out two years prior to the specified dates.

For this reason, published policy plans and technical brochures of industry manufacturers producing electrical switchgear are researched, with a focus on vacuum and CO_2/O_2 switchgear as these could lead to an earlier phase out of the C_4F_7N technology. The results of this research are shown in Table 6.2.2. Mitsubishi Electric, an electrical equipment manufacturer from Japan, primarily focusses on medium and low voltage distribution levels. Their highest rated vacuum switchgear operates at 72,5 kV, which falls short on the 145kV required for offshore converter stations. Toshiba, another Japanese manufacturer, produces vacuum switchgear under the brand Aorexia, in collaboration with Meidensha, which also manufactures vacuum switchgear independently, including model rated at 123kV and 145kV. However, their switchgear is insulated with SF_6 through which the GWP is not brought below 1. Iljin, South Korean company, collaborates with Siemens to produce a 170kV vacuum switchgear. Schneider Electric is constructing vacuum switchgear with air insulation, with a focus on low and medium voltage levels for distribution practices. Hyundai Electric manufactures both C_4F_7N and vacuum switchgear. In 2015, in collaboration with Korean electric power corporation (KEPCO), Hyundai Electric developed a 25,8 kV vacuum switchgear. By April 2021, they had constructed their first 170kV C_4F_7N switchgear. Addressing market demand, Hyundai Electric recently announced the development of a a 145kV GIS equipped with a vacuum interrupter.

While conducting research, no sources were found regarding the construction of CO_2/O_2 switchgear for high voltage applications. This may suggest that this technology is not widely produced or publicly known at this time. However, this assumption is based on the available literature and resources, and it could be possible that the technology is under development without public announcements. Following from the research, the number of expected companies that will construct sustainable high-voltage switchgear is limited. As it seems now, there are two companies most likely to construct a 145kV vacuum switchgear. The cooperation of Toshiba and Meidensha under the name Aeroxia could construct a vacuum switchgear for higher voltage levels. However, plans regarding this construction have not been announced yet. Hyundai Electric is most likely to develop a 145kV vacuum switchgear as they announced its development. Besides Siemens Energy, which is known for its vacuum switchgear, there could potentially be additional manufacturers for this technology for the second and third generation of platforms. The exact number, indicated as $N \geq 1$ in Table 6.2.1, may vary depending on the release dates of products from these manufacturers, which have not yet been announced.

Table 6.2.2: Electrical switchgear on the market with a GWP below 1 by manufacturers.

	MITSUBISHI ELECTRIC	TOSHIBA	MEIDEN	ILJIN	Schneider Electric	HD HYUNDAI ELECTRIC
Company name	Mitsubishi Electric	Toshiba	Meidensha	Iljin	Schneider Electric	Hyundai Electric
Technical brochure by capacity	72,5 kV	72,5 kV	123 / 145kV	170 kV	12 kV / 24 kV / 36 kV	25.8kV
Cooperating company	-	Meidensha	-	Siemens	-	KEPCO
Product line	-	Aeroxia	-	-	AirSeT	-
Insulation	Air	Air	SF_6	Air	Air	Dry air
Circuit breaker	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum

6.3 Answer to sub-question 4

This section reflects on the drivers and challenges and presents the most suitable type of switchgear. The vacuum and the CO_2/O_2 technology are preferred for implementation as they perform better in terms of GWP compared to C_4F_7N. There are three core factors that define the implementation of switchgear in future generation platforms.

First, the required capacity of electrical switchgear in future generation platforms is critical. The inter-array cables are expected to increase from 66kV for the first generation to 132kV for the second and third generation, but according to participant III, higher voltage levels are not expected. With 132kV inter-array cables, a 145 kV switchgear is sufficient. Siemens Energy already provides this for vacuum technology, but such a voltage level is not yet available for the CO_2/O_2 technology.

Second, the space requirement for switchgear is important given the limited space on the platform, and design adaptations are costly. With the number of bays reduced due to the 132kV inter-array cables, the total area required for vacuum switchgear becomes comparable to that of C_4F_7N installations in the first-generation platform, indicating no space constraints for vacuum switchgear. For CO_2/O_2 switchgear, there is no data available regarding installation sizes, but as it operates at higher pressure, the coatings are thicker which potentially increases the surface of the installation.

Third, the number of manufacturers for the vacuum and CO_2/O_2 technology is crucial. Regulation (EU) 2024/573 states that switchgears which rely upon an insulating or breaking medium with a GWP between 1 and 1000 are allowed if there is only one manufacturer offering an alternative with a GWP below 1. Currently, Siemens Energy is the sole provider of a 145kV switchgear with a GWP below 1. However, other manufacturers are likely to enter the market with similar offerings, which could make the C_4F_7N technology by General Electric and Hitachi Energy obsolete.

Considering these three core factors, vacuum switchgear emerges as the most suitable switchgear type for future generation platforms due to its compliance with electrical capacity, special, and regulatory requirements. C_4F_7N meets the criteria for capacity and space but faces regulatory challenges due to the expected increase in competitive alternatives following Regulation (EU) 2024/573.

6.4 Environmental impact comparison

In this section, the environmental impact of both the vacuum and C_4F_7N electrical switchgear is explored. While vacuum switchgear has been identified as the most suitable option for future generation platforms, Hitachi Energy and General Electric have independently researched high-voltage applications of C_4F_7N mixtures and are committed to continue their efforts to extend implementation. To clarify the motives for General Electric continuing its developments in C_4F_7N technology, an interview is conducted with the sustainability program leader of General Electric. According to participant IV, both General Electric and Hitachi Energy are convinced that the C_4F_7N switchgear is the most effective at reducing total emissions when compared to SF_6.

To validate this statement, studies on the environmental impact of 145kV electrical switchgear are reviewed. In previous chapters, the focussed was solely on the global warming potential and ozone depletion potential of specific gases to assess environmental impact. However, in this section, a more holistic view is considered as environmental impact in the system lifecycle are considered. In this study, the environmental impact is evaluated in CO2-equivalents in kg (GWP). Ozone Depletion Potential excluded because the gases SF_6 and C_4F_7N do not deplete the ozone layer, making ODP less relevant for this environmental impact comparison. Recent research by General Electric and Hitachi Energy (2023) identifies manufacturing and gas leakages during operation as the primary sources of CO_2 equivalent emissions. This section will delve into the environmental impacts associated with constructing and operating electrical switchgear. Due to the limited studies comparing the CO_2 emissions of vacuum, SF_6, and C_4F_7N switchgear, the following sub-question will be addressed:

SQ5: How do the environmental impacts of the alternatives compare during construction and operation?

This section compares the CO_2 equivalent emissions of SF_6, C_4F_7N, and vacuum switchgear during the manufacturing and use phase, as illustrated with yellow borders in Figure 6.4. For a cradle-to-cradle analysis, three phases are excluded in this study due to minimal emission differences among these switchgear types. Emissions in the distribution phase are similar for each switchgear type, although vacuum switchgear may produce slightly more CO_2 equivalents due to its increased weight compared to C_4F_7N and SF_6 installations. Installation emissions are considered equivalent across SF_6, vacuum and C_4F_7N installations due to similar installation procedures. End-of-life emissions are similar for the three switchgear types, though the SF6 installation could have higher CO_2 emissions due to potential leakages during dismantling, but this is carefully controlled. The distribution, installation, and end-of-life phases are not included in this environmental impact comparison as the focus is primarily on the manufacturing and product use phases, which are the main contributors of environmental impact.

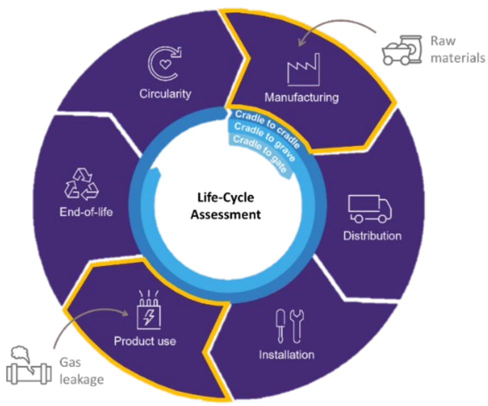

Figure 6.4: Phases of the Life-Cycle Assessment considered for the environmental impact assessment.

6.4.1 Manufacturing phase

The CO_2 emissions during the manufacturing phase are calculated based on the raw materials used in each switchgear type. For assessing the weight of each switchgear type, the technical brochures were consulted as shown in Table 3.4.3. While technical brochures provided the composition of materials, specific quantities were not listed. Two articles were identified that compared the composition of raw materials used in C_4F_7N and SF_6 switchgear, for which the results are shown in table D1 and table D2 in Appendix D. The raw materials which were addressed in the articles are aluminum, steel, copper, and epoxy. Although the actual weights of each material varied between the articles, the proportional ratios of the materials were similar. One article also assumed that the material ratio for vacuum switchgear is similar. For this research, the ratios from both articles were averaged, and the total weights were adjusted according to the installation weights as presented in the technical brochures by Siemens Energy, General Electric, and Hitachi Energy. The adjusted weights are shown in Table 6.4.1 (1) below.

Table 6.4.1 (1): Weight of a 145 kV switchgear, adjusted to the weights presented in technical brochures.

Raw materials	SF_6 [kg]	C_4F_7N mix [kg]	Vacuum [kg]	Percentage [%]
Aluminum	1926	2183	2847	64
Steel	794	900	1564	26
Copper	51	58	102	2
Epoxy	228	259	188	8
Total mass	3000	3400	4700	100

As the raw material composition of each switchgear type is defined, the total emissions can be calculated using the material specific CO_2 equivalent. The carbon footprint of each material, and the total emissions for each switchgear are presented in Table 6.4.1 (2). Aluminum production is for all the installations the biggest source of equivalent CO_2 emissions.

Table 6.4.1 (2): Equivalent CO_2 emissions from manufacturing of each 145kV switchgear type.

Raw materials	[kg CO_2] / [kg material]	SF_6 [kg CO_2]	C_4F_7N [kg CO_2]	Vacuum [kg CO_2]
Aluminum	15,1 (IAI, 2024)	29089	32968	42983
Steel	1,4 (IEA, 2023)	1112	1260	2190
Copper	4,1 (Mansell, 2023)	209	237	417
Epoxy	4,8 (CarbonCloud, 2024)	1097	1243	901
Total mass	-	31507	35708	46491

6.4.2 Use phase

The equivalent CO_2 emissions during the use phase are defined based on the installation lifetime, the amount of gas per installation, the gas leakage rate for each installation, and the GWP of each gas. The lifetime of the installations is the same for all types, each designed for an operation time of 40 years. According to participant II, General Electric ensures a maximum yearly leakage of 0.1% for the SF_6 switchgear and 0.5% for the C_4F_7Nswitchgear, which are taken as the reference. The amount of gas in each installation is presented by General Electric and Hitachi (2023) to be 64 kg for SF_6, 31 kg for C_4F_7N, and 32 kg for vacuum. Although the pressure in the $C_4F_7N$and vacuum installations are higher compared to the SF_6 installations, the total gas weight is lower because of their lower molecular weights. Vacuum switchgear is isolated with clean air, which has a molar mass of 28.97 (Gatley et al., 2008). The molar mass of C_4F_7N is dependent on the mixture ratio and is presented in formula [8]. When the temperature, the gas constant and the volume stay the same, and only the pressure increases, the number of molecules increases following the ideal gas law.

$$n = \frac{PV}{RT} \quad [7]$$

The mass of the C_4F_7N mixture is dependent on the ratio and the individual molecular masses. The molar mass of molecule C_4F_7N is 195 g/ mol (3M, 2022). The mixture used in C_4F_7Ninstallations typically contains 4% to 6% of the molecule C_4F_7N (Smeets, 2022). The mixture with molar percentages of 6% C_4F_7N, 5% O_2 and 89% CO_2 is chosen as a reference. The mass of the mixture is presented in formula [8], depending on the number of molecules. The mass of SF_6 does not consist of a mixture and is presented in formula [9]. When the pressure for SF6 operates at 5 bar, and the C_4F_7N at 7 bar, the gas weight for the C_4F_7N installation is about half the weight of the SF_6 gas.

$$Mass_{C4-FN\ mixture} = 0.06 * 195 * n + 0.05 * 32.0 * n + 0.89 * 44.01 * n = 52{,}47n \quad [8]$$

$$Mass_{SF6} = 1.00 * 146.06 * n = 146.06n \quad [9]$$

The global warming potential for the C_4F_7N mixture is calculated using formula [2] as described in section 4.2.1. The same mixture ratio is considered.

$$GWP_{C4-FN\ mixture} = \frac{0.06 * 195 * 2750 + 0.05 * 32.0 * 0.0 + 0.89 * 44.01 * 1.0}{0.06 * 195 + 0.05 * 32.0 + 0.89 * 44.01} = 614 \quad [10]$$

The total yearly gas leakage in kg CO_2 equivalents is calculated using formula [11] and is presented in table 8 for each type of switchgear. An equal distribution of the gas leakage is assumed over the lifetime.

$$Yearly\ gas\ leakage = Gas\ per\ installation * Gas\ leakage\ rate * GWP_{100} \quad [11]$$

Table 6.4.2: Parameters for the use phase calculation

Parameter	SI unit	SF_6	C_4F_7N mix	Vacuum
Product lifetime	[years]	40	40	40
GWP_{100}	[kg CO_2 eq.]	24300	614	0
Leakage rate	[% per year]	0.1	0.5	1
Gas per installation	[kg]	64	31	32
Molecular weight	[g/mol]	146.06	52.47	28.97
Yearly CO_2 gas leakage	[kg CO_2 / year]	1555.2	95.2	0
Pressure in installation	[bar]	5	7	7

6.4.3 Answer to sub-question 5 for the first generation platform

The total CO_2 emissions during the manufacturing phase and the use phase over the installation lifetime is presented in Figure 6.4.2. For the first-generation platform, a total of 40 electrical switchgear installations are deployed, for which both the manufacturing and use phase are multiplied by 40. A reduction of CO_2 equivalent emission is observed when the SF_6 installation is compared to the C_4F_7N and vacuum installations, which can be explained through the high global warming potential of SF_6. When comparing the C_4F_7N installation and the vacuum installation, the C_4F_7N shows lower total CO_2 equivalent emissions. The largest share in terms of CO_2 equivalents for both installations is the aluminum production.

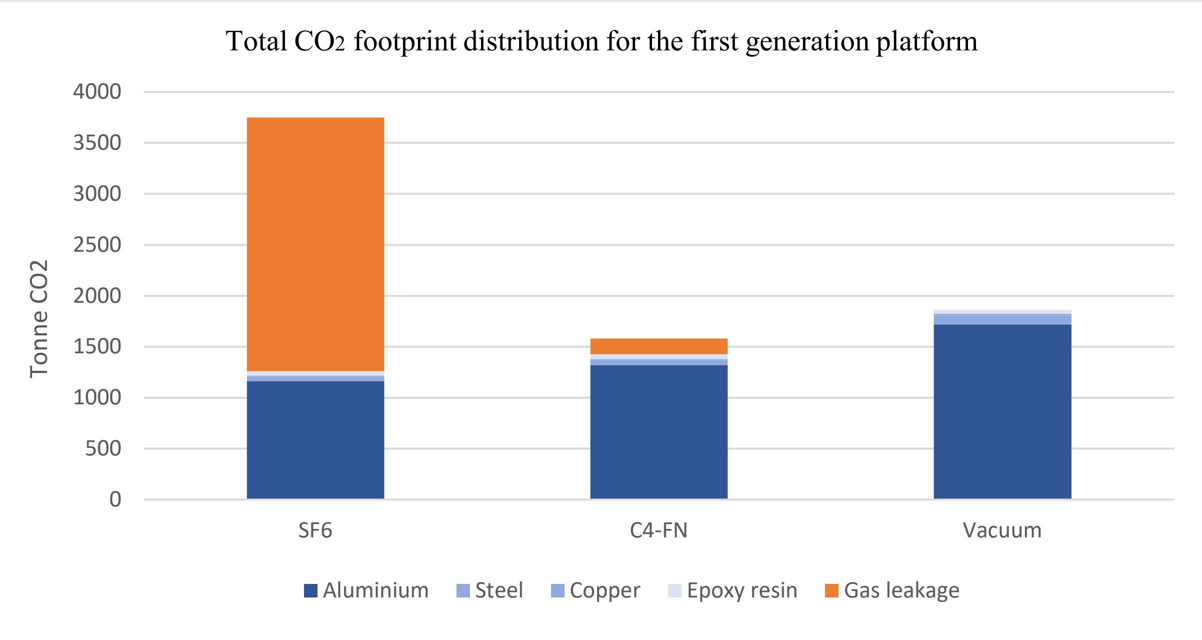

Figure 6.4.3: Total CO_2 equivalent emissions for 40 electrical switchgear installations.

6.4.4 Answer to sub-question 5 for the second generation platform

The switchgear types for the first-generation platforms are already fixed as discussed in section 6.2.1. For this reason, it is interesting to consider the environmental impact for the second-generation platform. For the second-generation, the same 145kV installations are being installed and the number of installations is reduced from 40 to 28, which ensures a CO_2 equivalent reduction of 30% for all installations. The equivalent CO_2 emissions over the 40-year lifetime are presented in Figure 6.4.4 (1).

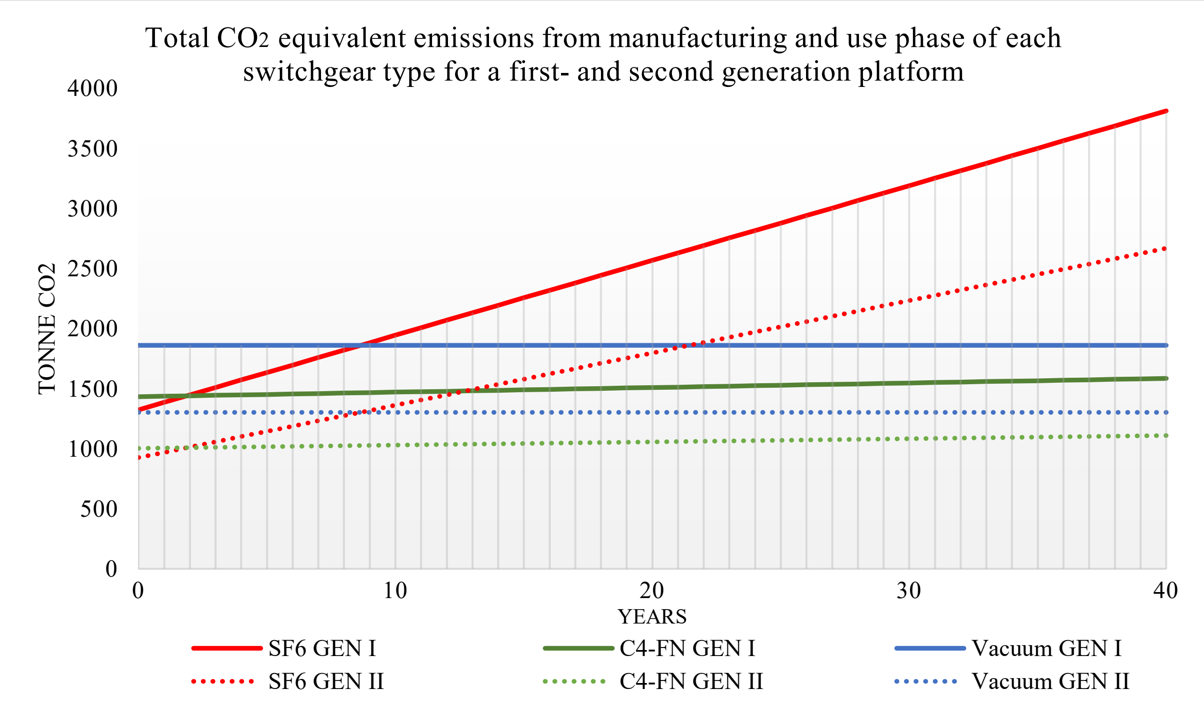

Figure 6.4.4 (1): CO_2 equivalent emissions over 40 years for first-generation and second-generation SF_6, C_4F_7N, and vacuum switchgear.

The total CO_2 equivalent emissions are reduced for the second-generation platform, but the order is not affected since the reduction is proportionally the same for all switchgear types. The aluminum production is still the main source of CO_2 emittance, as presented in Figure 6.4.3. The second-generation platforms are constructed between 2033 and 2037, for this reason the expected emissions from aluminum production must be considered. According to the International Aluminum Institute (2024), China accounts for about 60% of the total primary aluminum production, which is presented in figure D1. The average CO_2 emittance for primary aluminum production varies for each country and is based on a country's energy mix, this is presented in figure D2. The primary aluminum production in China is in the range of 15-to-18-ton CO_2 per ton aluminum. For some European countries like France, Sweden, and Norway, the primary aluminum production is in the range of 3-to-6-ton CO_2 per ton aluminum. This can be explained due to the lower CO2 emissions in these countries' energy mix, primarily driven by hydropower and nuclear power. China, being the largest primary aluminum producer, announced a plan to expand the national energy trading system (ETS) (International Carbon Action Partnership, 2024). The plan proposes to extend the ETS to include the steel, cement, and aluminum industries, which puts pressure for these industries to reduce emissions. Globally, the aluminum intensity has been decreased by an average of 1.45% between 2010 and 2022 (International Energy Agency, 2023). If this trend were to continue until 2035, driven by the plans of the revised ETS system in China, innovation, and the global shift towards a more sustainable energy mix, the global average aluminum intensity for 2035 would be 11.7 tons of CO_2 per ton of aluminum, as presented in figure D3. Reducing the primary aluminum intensity leads to a greater percentage reduction in the total CO_2 equivalent emissions for the vacuum switchgear compared to the SF_6 and C_4F_7N installations, as the total emissions for vacuum switchgear consist almost entirely on aluminum production as shown in Figure 6.4.4 (2). The emittance during the manufacturing phase with a global average reduction in aluminum intensity is presented in table D3. The total emissions for the switchgear installations are presented in Figure 17, with aluminum intensities for 2022 and the expected 2035 values. The total emittance of the vacuum installations is still higher compared to the C_4F_7N installations. The vacuum installation is becoming competitive in terms of total CO_2 emissions with an aluminum intensity equal or below 4.5 kg CO_2 per kg aluminum, as presented in Figure 6.4.4 (3). This aluminum intensity is possible, as shown by France, Norway and Sweden, but the global average is still significantly higher. Therefore, the C_4F_7N installation is regarded as the switchgear type with the lowest total CO_2 equivalent emissions during the manufacturing and use phases for both first- and second-generation platforms.

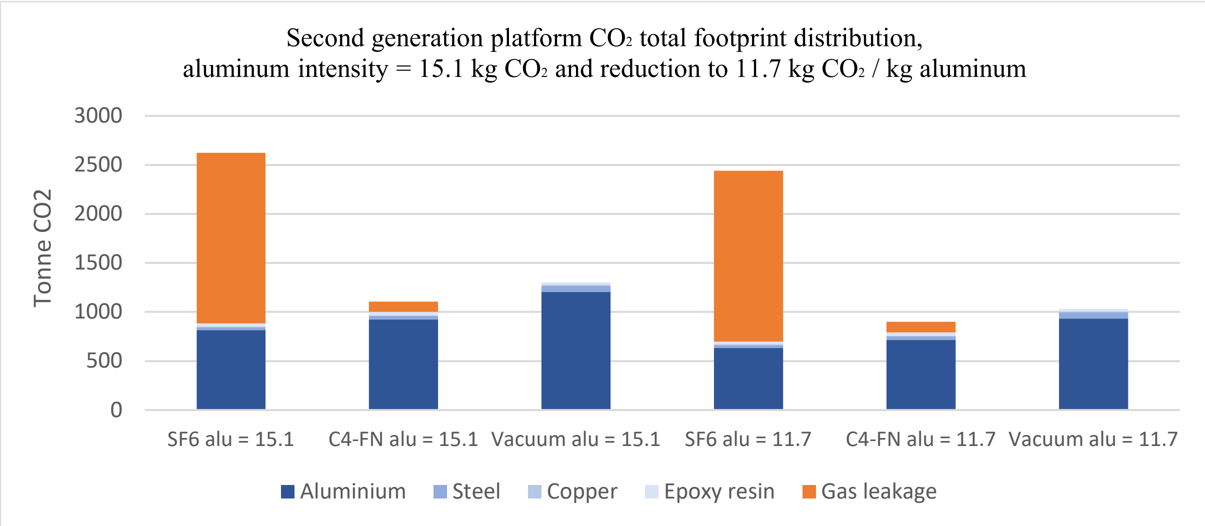

Figure 6.4.4 (2): Aluminum intensity comparison for second generation platform.

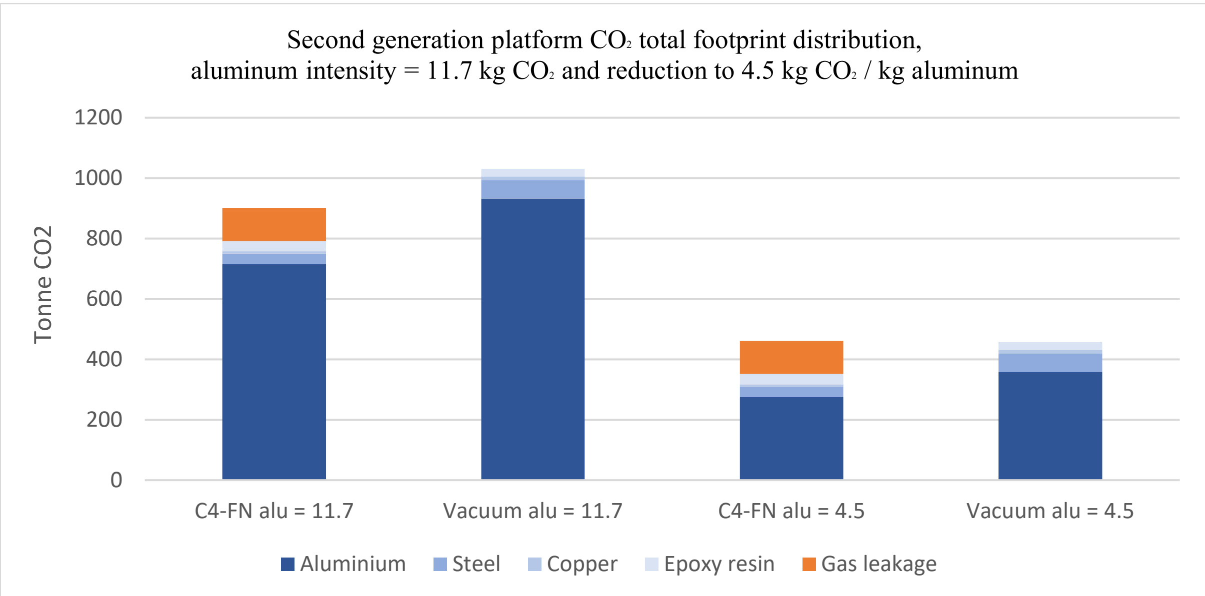

Figure 6.4.4 (3): The total emissions from the vacuum installation are lower for an aluminum intensity below 4.5.

7. Conclusion, policy recommendations, and future research

This study focusses on identifying a more sustainable alternative to SF_6 for the application in electrical switchgears for offshore converter stations. This research was performed by describing the current state of the offshore wind sector, determining the relevant criteria for the alternative gases, identifying the most suitable alternatives, examining the future viability of the alternatives, and concluding with a comparison regarding installation sustainability. In this chapter the conclusion of this study is drawn in section 7.1, followed by policy recommendations for TenneT, as well a suggested adaptations to regulations in section 7.2. The chapter concludes with a reflection on the results and proposes further research based on the insights gained from the discussion in section 7.3.

7.1 Conclusion

The primary research question which is addressed in this study is:

What is the most viable alternatives to SF_6 in high-voltage switchgear for offshore converter stations, and how can its implementation be aligned with future platform developments and regulatory frameworks?

To determine the most viable alternatives to SF_6, potential technologies were evaluated based on the criteria boiling point, dielectric strength, toxicity, flammability, ozone depletion potential, and global warming potential. Following from Regulation (EU) 2024/573, three distinct markets emerge, as presented by the red, orange, and green colours in Figure 7.1. The first market is the current market without GWP restrictions. The second market represents a transitional phase characterized by a GWP between 1 and 1000, applicable over a period of two years. The third market comprises alternatives that exhibit a GWP less than 1. In this study, the most suitable alternatives for the second and third markets were identified. For the second market with a GWP between 1 and 1000, a mixture of C_4F_7N with non-synthetic gases was found as the sole alternative meeting all the criteria. For the market with a GWP less than 1, two theoretical alternatives exist. The first utilizes non-synthetic gases for insulation and interruption at pressure levels ranging from 12 to 15 bar. While theoretically possible, developing coatings that can withstand these pressures presents significant challenges. The second alternative involves a vacuum circuit breaker with clean air insulation. This technology has been widely adopted for low and medium voltage levels and is also adopted for high voltage levels up to 145kV. This capacity is sufficient for future platform innovations, and fits on the existing platform in terms of dimensions of the installation. Currently, Siemens Energy is the sole provider of 145kV vacuum switchgear, but Toshiba and Hyundai Electric are likely to develop this technology soon. As more suppliers emerge, the industry will shift towards vacuum switchgear for future generation offshore converter stations.

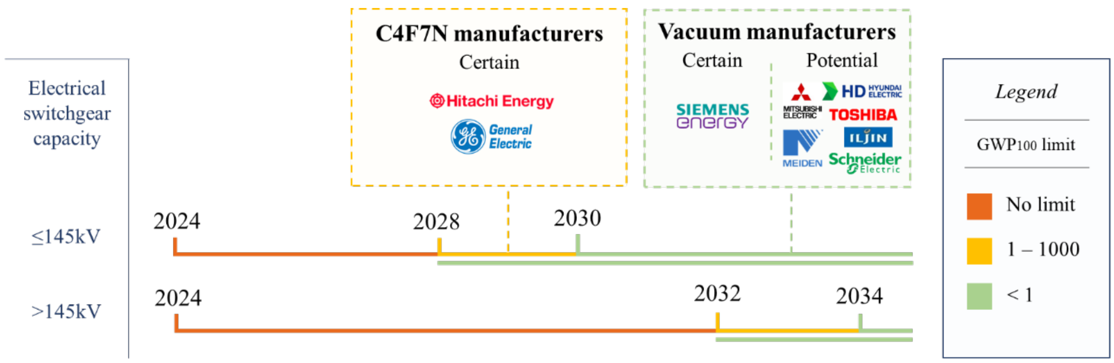

Figure 7.1: Timeline for reducing high-voltage switchgear GWP under Regulation (EU) 2024/573 and potential manufacturers.

Regulation (EU) 2024/573 requires a shift to high-voltage switchgear with a global warming potential below 1. Currently, Siemens Energy is the sole manufacturer of 145kV switchgear that meets this criterion. As shown in Figure 7.1, for switchgear up to and including a capacity up to 145kV, all alternatives with a GWP above 1 become obsolete from 2030. General Electric and Hitachi Energy produce switchgear with a GWP between 1 and 1000, which can be installed until 2028, possibly extending to 2030 if Siemens Energy remains the sole provider. If just one additional manufacturer develops a 145kV switchgear with a GWP below 1, which results in more then one manufacturer of vacuum switchgear, installing C_4F_7N switchgear will be prohibited. When future generation platforms would require a 170kV switchgear, similar rules apply but with adjusted timelines. This means that for the second-generation platforms a 170kV C_4F_7N switchgear could be installed between 2032 and 2034, if there is just one manufacturer of a 170kV vacuum switchgear. After 2034, all switchgear installations must has a GWP below 1. This could be CO_2/O_2 installations or vacuum installations, where vacuum is most likely due to current technological advancements and space constraints.

To align with regulatory frameworks, vacuum switchgear is currently the most suitable option following Regulation (EU) 2024/573, as the vacuum technology is available up to 145kV and presents a GWP less than 1. However, the life-cycle emissions of the switchgear yet not considered in this regulation. As a result of this study, tit has been demonstrated that C_4F_7N exhibits lower total emissions compared to the vacuum switchgear during the manufacturing and use phases, which are identified as having the most significant impact on the total life cycle emissions of the switchgear. A reflection on the impacts of Regulation (EU) 2024/573 will be published on January 1, 2030. Potentially, this reflection could require a comprehensive life-cycle assessment to determine the most sustainable switchgear alternative.

7.2 Policy recommendations

This section presents recommendations for TenneT along with proposed regulatory adaptations aimed at enhancing the sustainability of future offshore converter stations.

7.2.1 Policy recommendations for TenneT

TenneT's first-generation 2GW platform aims to create a universal design suitable for all sites. However, due to Regulation (EU) 2024/573, necessary adjustments must be made to the electrical switchgear. The first-generation Dutch platforms currently use the C_4F_7N mixture, which remains compliant for this generation as orders have been placed before the new regulation was announced. For the second-generation platform, which will be built between 2032 and 2037, substantial design changes are required. Given that Siemens Energy already provides electrical switchgear with a GWP below 1, the 145kV C_4F_7N technology may no longer be installed from 2030 onwards. One option for TenneT is to consider 170kV switchgear, which can still utilize the C_4F_7N mixture until 2032. This can be extended to 2034 if Siemens will remain the only manufacturer of a 170kV switchgear with a GWP below 1.

Nevertheless, since 2034 is close to the start of the second-generation timeline, it is unlikely that the platform will be built in this year. Therefore, TenneT should proactively transition towards alternatives with a GWP below 1 for the second-generation platforms. The current generation platform is designed using 66kV inter array cables, but adopting 132kV cables would reduce the number of switchgears from 40 to 24. This shift would enable vacuum switchgear to fit within the existing design space, with a similar spatial footprint to the 40 C_4F_7N installations currently planned. The first-generation platforms constructed by Siemens Energy in Germany can serve as example, as vacuum switchgear is already implemented in these platforms. It is recommended for TenneT to facilitate knowledge sharing between these existing projects to streamline the transition towards vacuum switchgear.

7.2.2 Policy recommendations for the European Commission

To support the goal of the European Union to reduce greenhouse gas emissions by 55% in 2030 compared to 1990 levels and achieving climate neutrality by 2050, electrical switchgear designs must prioritize minimal emissions. While Regulation (EU) 2024/573 targets reducing fluorinated gases and their global warming potential, it overlooks the total ecological footprint of switchgear installations. Notably, aluminum production significantly increases the total emissions. With China accounting for 60% of global primary aluminum production, it heavily influences the global average aluminum intensity. Vacuum switchgear could become the most sustainable alternative to SF_6, but this is dependent on the aluminum intensity. However, current regulations, including Regulation (EU) 2024/573, do not incentivize sustainable aluminum production, leading manufacturers to choose for the cheapest instead of the most sustainable option available. According to Directive 2009/125/EC, which sets a framework for eco-design of energy-related products, the most sustainable switchgear type must present the lowest total emissions over the product life cycle. This study shows that vacuum switchgear, despite its advantages, poses a greater environmental impact over tis life cycle due to its higher aluminum content compared to C_4F_7N installations. Although a shift towards renewable energy may reduce the aluminum intensity, vacuum switchgear is still projected to have a higher environmental impact by 2035 than C_4F_7N.

Therefore, it is recommended to integrate life cycle assessments (LCA) within the regulatory framework to accurately measure and compare the total equivalent emissions of switchgear alternatives. If LCAs show that C_4F_7N switchgear results in lower overall emissions than vacuum switchgear, its use should not be restricted. This approach would serve as an incentive for the vacuum switchgear manufacturers to reduce their aluminum intensity.

7.3 Discussion and further research

This section evaluates the assumptions made in this study and their impact on the results. The study was performed in collaboration with TenneT in the Large Project Offshore department, in the cluster of General Electric Seatrium. A first challenge could be seen in the collaboration with General Electric, being one of the contractors. To mitigate this, the system context was described including the German projects of TenneT to put forward the other contractors. The interview for describing the system context was conducted with a TenneT employee outside the General Electric Seatrium cluster to minimize interests.

A second challenge could occur in the selection of possible alternatives. To ensure a comprehensive evaluation of alternatives, research was conducted covering manufacturing companies across all voltage levels. This approach aimed to include potential alternatives that might only be produced by companies specializing in lower voltage ranges. Some alternatives received more interest in academic literature in recent years, but in this study specific attention has been given to alternatives with a global warming potential in the range of 1000, as this limit was just introduced in February 2024.

A third challenge could be observed in the environmental impact comparison. The input variables were found in articles published by General Electric, Hitachi Energy and Hyundai Energy, who are all manufacturers of the C_4F_7N technology. Notably, there was a lack of reliable information on the raw material composition of vacuum switchgear, leading to assumptions based on competitor publications. To provide a more accurate environmental comparison between vacuum and C_4F_7N switchgear, data published by Siemens should be included as well. In addition, the analysis focused only on the manufacturing and use phases, as these were defined having the highest greenhouse gas emittance during the product lifecycle. For a total environmental comparison between a vacuum and C_4F_7N switchgear, further research should conduct a full life cycle assessment. Ideally, that research should be carried out by an independent third party to ensure neutrality, as current available literature is only produced by constructors themselves.

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Appendix A. Literature review

A.1 Literature selection process

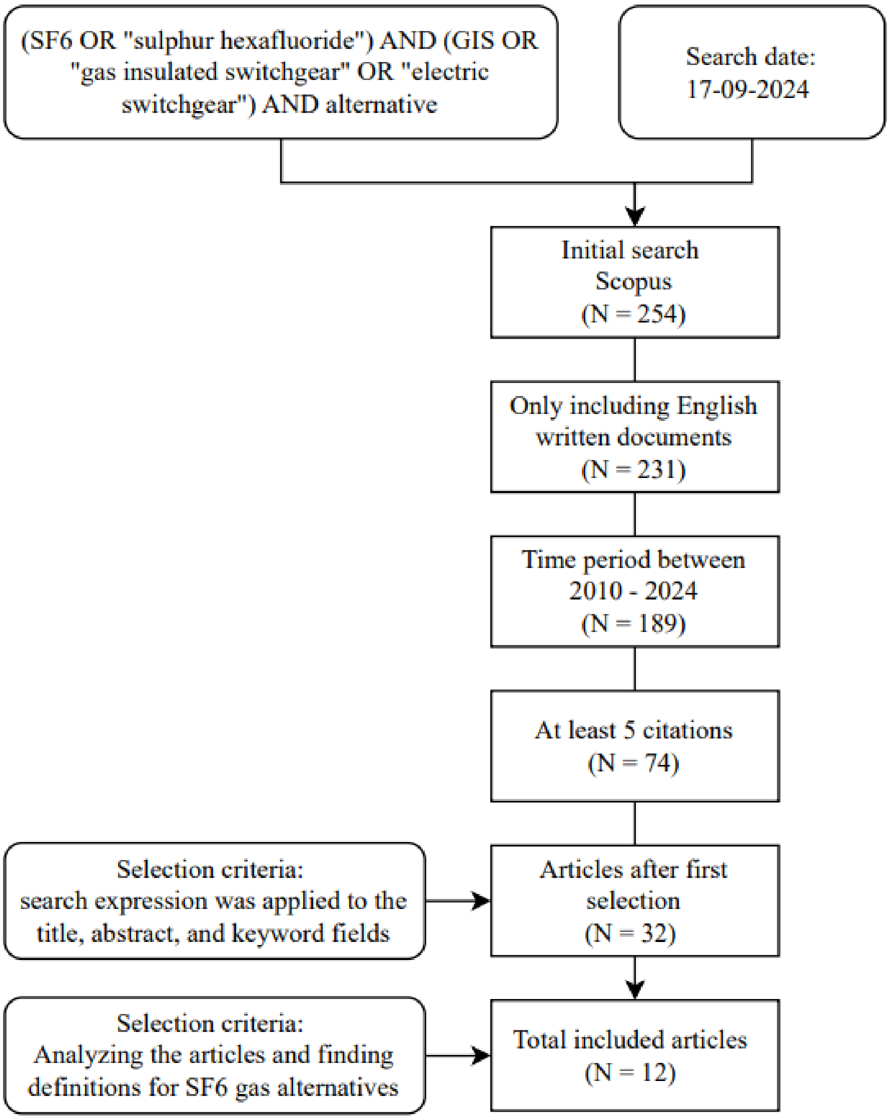


Figure A1: Literature selection process

A.2 Selected articles for literature review

Table A.2: Overview of literature for critical review

Article Title	Authors	Publication
Study on oxygen/nitrogen gas mixtures for the surface insulation performance in gas insulated switchgear	Lim, D.-Y., Bae, S.	2015
SF6 alternative development for high voltage switchgears	Kieffel, Y., Girodet, A., Biquez, F., (...), Van San, R., Werner, K.	2014
Advanced insulation and switching concepts for next generation High Voltage Substations	Presser, N., Orth, C., Lutz, B., Kuschel, M., Teichmann, J.	2016
Recent advances in the quest for a new insulation gas with a low impact on the environment to replace Sulfur Hexafluoride (SF6) gas in high-voltage power network applications	Beroual, A., Haddad, A.	2017
Dielectric strength of SF6 substitutes, alternative insulation gases and PFC-gas-mixtures	Hopf, A., Britton, J.A., Rossner, M., Berger, F.	2017
SF6 alternative development for high voltage Switchgears	Kieffel, Y., Biquez, F., Ponchon, P., Irwin, T.	2015
Holistic evaluation of the performance of today's SF6 alternatives proposals	Kosse, S., Nikolic, P.G., Kachelriess, G.	2017
SF6-alternative gases for application in gas-insulated switchgear	Li, X., Zhao, H., Murphy, A.B.	2018
Environmental and physiochemical properties of gaseous dielectrics alternatives to sf6	Düzkaya, H., Tezcan, S.S., Acartürk, A., Yilmaz, M.	2020
Partial discharge behavior of protrusion on high voltage conductor in GIS/GIL under high voltage direct current: Comparison of SF6 and SF6 alternative gases	Toigo, C., Vu-Cong, T., Jacquier, F., Girodet, A.	2020
Recent development of two alternative gases to SF6 for high voltage electrical power applications	Owens, J., Xiao, A., Bonk, J., De Lorme, M., Zhang, A.	2021
Replacing SF6 in electrical gas-insulated switchgear: Technological alternatives and potential life cycle greenhouse gas savings in an EU-28 perspective	Billen, P., Maes, B., Larrain, M., Braet, J.	2020

A.3 Regulation EU 2024/573 citations of relevant articles

9. The putting into operation of the following electrical switchgear using, or whose functioning relies upon, fluorinated greenhouse gases in insulating or breaking medium shall be prohibited as follows:

(a) from 1 January 2026, medium voltage electrical switchgear for primary and secondary distribution up to and including 24 kV;

(b) from 1 January 2030, medium voltage electrical switchgear for primary and secondary distribution from more than 24 kV up to and including 52 kV;

(c) from 1 January 2028, high voltage electrical switchgear from 52 kV up to and including 145 kV and up to and including 50 kA short circuit current, with a global warming potential of 1 or more;

(d) from 1 January 2032, high voltage electrical switchgear of more than 145 kV or more than 50 kA short circuit current, with a global warming potential of 1 or more.

11. By way of derogation from paragraph 9, the putting into operation of electrical switchgear using or whose functioning relies upon insulating or breaking medium with a global warming potential lower than 1 000 is allowed if, following a procurement procedure that considers the technical specificities of the equipment required for the specific use concerned one of the following situations applies:

(a) during the first 2 years after the relevant dates referred to in paragraph 9, points (a) and (b), no bids or only bids offering equipment from one manufacturer of electrical switchgear with insulating or breaking medium not using fluorinated greenhouse gases were received;

(b) during the first 2 years after the relevant dates referred to in paragraph 9, points (c) and (d), no bids or only bids offering equipment from one manufacturer of electrical switchgear with insulating or breaking medium with a global warming potential of less than one was received;

(c) after the 2-year period referred to in point (a), no bids were received offering equipment from one manufacturer of electrical switchgear with insulating or breaking medium not using fluorinated greenhouse gases; or

(d) after the 2-year period referred to in point (b), no bids were received offering equipment from one manufacturer of electrical switchgear with insulating or breaking medium with a global warming potential of less than one.

12. By way of derogation from paragraph 11, the putting into operation of electrical switchgear with insulating or breaking medium with a global warming potential of 1 000 or more is allowed if, following a procurement procedure that considers the technical specificities of the equipment required for the specific use concerned, no bid was received for electrical switchgear with insulating or breaking medium with a global warming potential of less than 1 000.

14. Paragraph 9 shall not apply where the operator can provide evidence that the order for the electrical switchgear has been placed before 11 March 2024.

5. By 1 January 2030, the Commission shall publish a report on the effects of this Regulation. The report shall include an evaluation of the following:

(e) the risk of excessive reduction of competition in the market due to the prohibitions and related exceptions under Article 13(9), in particular those on high voltage electrical switchgear of more than 145 kV or more than 50 kA short circuit current.

A.4 European and Dutch regulations on fluorinated greenhouse gases

Table A.4: European norms and regulations regarding fluoride gases

EU regulation on F-gases	
EU517/2014	Regarding Fluoride Greenhouse Gases, protection environment
EU2015/2016	Certification for people working with SF_6
EG166/2005	European Register for transfer and emission of pollutant substances
PRTR	Pollutant Release and Transfer Register
EU1191/2014	Commissioning EU517/2014
EU1497/2007	Labels on products that contain F-gases
EN62271-4	handling procedures for SF_6

International electrotechnical norms IEC regarding SF_6	
IEC 60376	Quality grade for SF_6
IEC 60480	Guidelines for checking and treatment of SF_6
IEC 62271-4	SF_6 handling procedures

Dutch rules and regulations on F-gases	
NEN-EN-IEC 62271-4	Acceptation of SF_6 handling procedures
30973/2015 Staatscourant	Leakage detection system has to be checked once in 6 years
Gaswet	Execution EU517/2014
Bekendmakingen	Phasing out F-gases for the ozone-layer
PRTR in SC	Execution PRTR, maximum SF_6 leakage per year
Protocol 12-026 Sterkstroom	Yearly SF_6 quantity determination
BRL200	Examination for people working with SF_6

Appendix B. Single line diagram

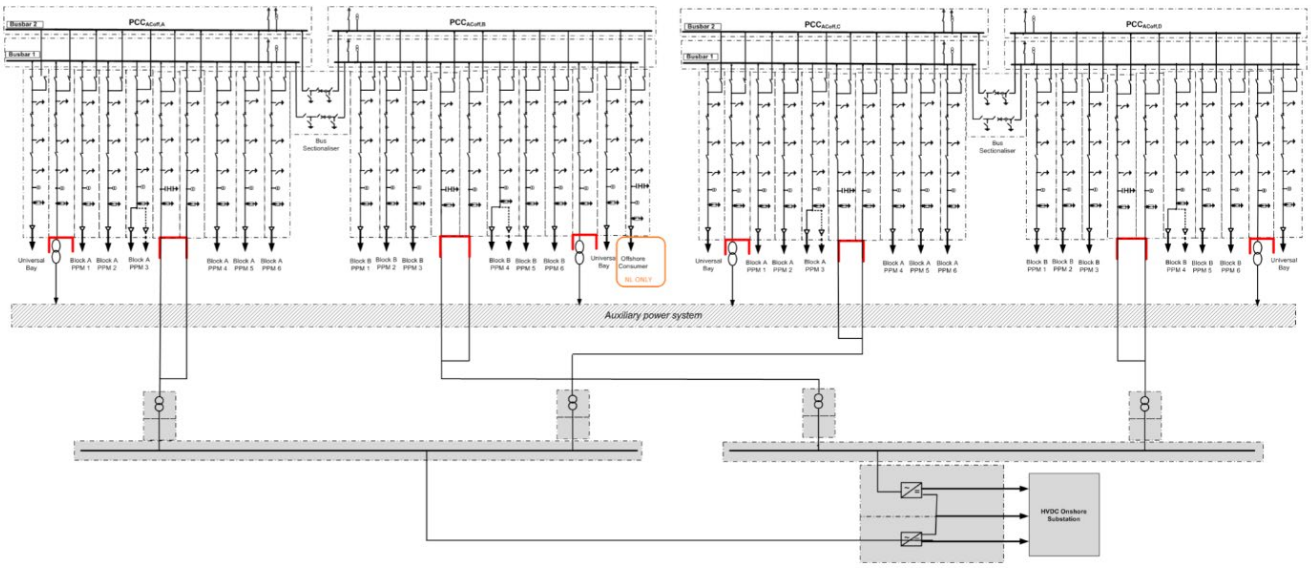


Figure B1: Single line diagram of electrical switchgear installations in the first-generation converter station.

Appendix C. Evaluation of alternatives

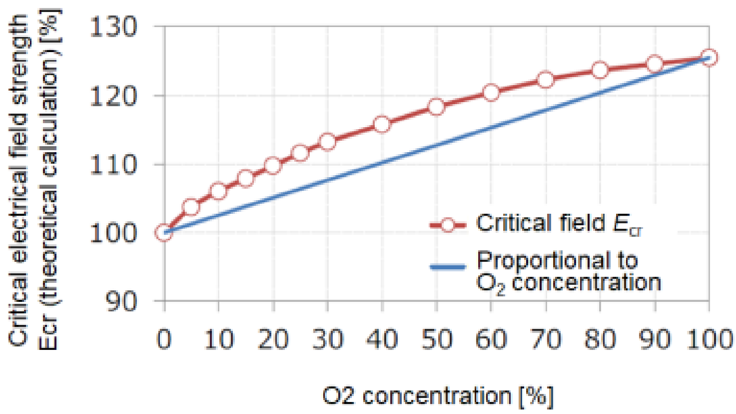
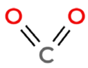
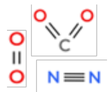
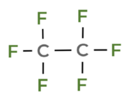
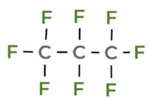
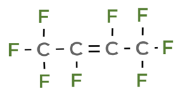
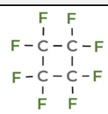
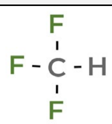
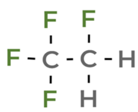
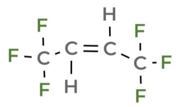
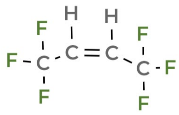
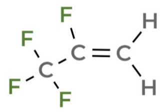
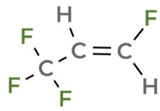
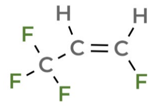
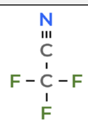
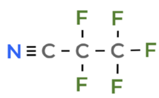
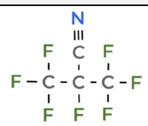
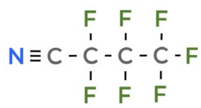
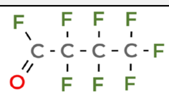
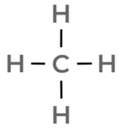
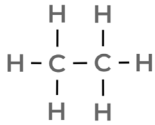
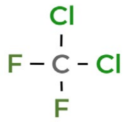
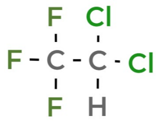


Figure C.1: The effect of O_2 concentration on the dielectric strength of CO_2.

Table C.1: Gas characteristics of promising alternatives for SF_6

Non-Synthetics	CO_2	N_2	Air	O_2	
Molecular structure					
GWP	1	0 (Ullah et al. 2018)	<1	<1	
Boiling point	-79 (Romero et al, 2017)	-196 (Ullah et al, 2018)	-193 (Ullah et al, 2020)	-183 (PubChem)	
Toxicity LC_{50}	300.000 (Romero et al, 2017)	Non-toxic (Dincer et al, 2021)	Non-toxic	Non-toxic (Dincer et al, 2021)	
Flammability	No (Smeets et al., 2023)	No	No	No	
Dielectric strength	0.30-0.40 (Chen et al, 2019)	0.34.0.43 (Ullah et al, 2018)	0.37-0.40 (Ullah et al, 2020)	0.33-0.37 (Dincer et al, 2021)	
Fluorocarbons	CF_4	C_2F_6	C_3F_8	C_4F_8	c-C_4F_8
Molecular structure					
GWP	6500 (Beroual, 2017)	9200 (Beroual, 2017)	7000 (Beroual, 2017)	8700 (Beroual, 2017)	8700 (Ullah et al, 2020)
Boiling point	-128 (Beroual, 2017)	-78 (Beroual, 2017)	-36.6 (Beroual, 2017)	-6 (Beroual, 2017)	-8 (Ullah et al, 2020)
Toxicity	Low toxic (Beroual, 2017)	Non-toxic (Beroual, 2017)	Non-toxic (Beroual, 2017)	Non-toxic (Beroual, 2017)	Non-toxic
Flammability	n.a.	n.a.	n.a.	n.a.	n.a.
Dielectric strength	0.4 (Ullah et al, 2020)	0.76 (Ullah et al, 2020)	0.88 (Beroual, 2017)	1.11-1.80 (Beroual, 2017)	1.2-1.3 (Ullah et al, 2020)
Hydrofluorocarbons	CHF_3	$C_2H_2F_4$			
Molecular structure					
GWP	14.800 (IPCC, 2007)	1300 (Ullah et al, 2018)			

Boiling point	-82 (PubChem)	-26 (Ullah et al, 2018)			
Toxicity	n.a.	Non-toxic (Ullah et al, 2018)			
Flammability	n.a.	No (Ullah et al, 2018)			
Dielectric strength	0.29 (Berger, 1998)	0.85 (Ullah et al, 2018)			
Hydrofluoroolefins	$C_4H_2F_6$ R1336mzz (E)	$C_4H_2F_6$ R1336mzz (Z)	$C_3H_2F_4$ R1234yf	$C_3H_2F_4$ R1234ze (E)	$C_3H_2F_4$ R1234ze (Z)
Molecular structure					
GWP	18 (Ahmed et al, 2023)	2 (Juhasz, 2017)	1 (Juhasz, 2017)	6 (Fukunda, 2013)	6 (Izagirre, 2022)
Boiling point	7.5 (Ahmed et al, 2023)	33.4 (Ahmed et al, 2023)	-29.5 (Juhasz, 2017)	-19 (Fukunda et al, 2013)	9.8 (Fukunda et al, 2013)
Toxicity	No (Juhasz, 2017)	n.a.	405.000 (Preve et al, 2015)	207.000 (Preve et al, 2015)	n.a.
Flammability	No (Juhasz, 2017)	n.a.	Mildly (Preve et al, 2015)	No (Preve et al, 2015)	n.a.
Dielectric strength	n.a.	2 (Ahmed et al, 2023)	n.a.	0.7 (Soulie, 2022)	0.8 (Izagirre, 2022)
Fluoronitriles	CF_3CN	C_2F_5CN	C_3F_7CN	C_4F_7N	
Molecular structure					
GWP	1030 (Andersen et al, 2022)	1800 (IPCC, 2021)	2100 (IPCC, 2021)	2750 (IPCC, 2021)	
Boiling point	-62 (Beroual, 2017)	-32 (Beroual, 2017)	-2 (Beroual, 2017)	-4.7 (Pan et al, 2020)	
Toxicity	Highly (Beroual, 2017)	Highly (Beroual, 2017)	Toxic (Beroual, 2017)	10.000-15.000 (Kieffel, 2014)	
Flammability	n.a.	n.a.	n.a.	No (Pan et al, 2020)	
Dielectric strength	1.34-1.40 (Beroual, 2017)	1.80-1.85 (Beroual, 2017)	2.20-2.33 (Beroual, 2017)	2.00-2.20 (Romero et al, 2017) (Kieffel, 2014)	
Fluoroketones	C_4F_8O	$C_5F_{10}O$	$C_6F_{12}O$		
Molecular structure					
GWP	13.900 (IPCC, 2021)	< 1 (Zhang et al, 2017)	< 1 (IPCC, 2024)		
Boiling point	0 (Kieffel, 2024)	27 (Kieffel, 2024)	49.2 (Beroual, 2017)		
Toxicity	20.000 (Hyrenbach & Zache, 2016)	20.000 (Preve et al, 2015)	100.000 (Kieffel, 2014)		
Flammability	n.a.	No (Owens et al, 2021)	No (Mantilla et al, 2014)		
Dielectric strength	n.a.	2.0 (Chen et al, 2019)	1.7 - 2.8 (Kieffel, 2014) (Chen et al, 2019)		

Hydrocarbons and Chlorocarbons	CH_4	C_2H_6	CF_2 Cl_2	CF_3 $CHCl_2$
Molecular structure				
GWP	25 (IPCC, 2007)	10 (Hodnebrog et al, 2018)	10.200 (IPCC AR5, 2013)	23 (Juliandhy et al, 2018)
Boiling point	-161 (ICSC, 2021)	-84 (Verschueren, 2001)	-29.8 (Pubchem n.d.)	28 (Pubchem, n.d.)
Toxicity	57.000 (Regulation (EC) No. 1907/2006)	80.000 (Linde, 2016)	800.000 (A-Gas Australia Pty Ltd, 2022)	32.000 (Pubchem, n.d.)
Flammability	Highly (Unacademy, 2022)	Highly (Unacademy, 2022)	No (Pubchem n.d.)	No (Pubchem n.d.)
Dielectric strength	0.4 (Berger, 1998)	n.a.	0.9 (Kharal et al, 2019)	1.3 (Juliandhy et al, 2018)

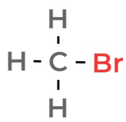
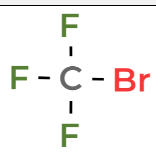
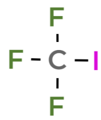
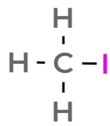
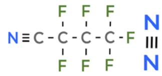
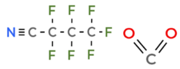
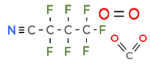
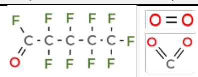
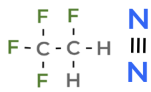
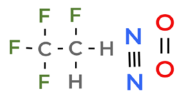
Bromocarbons & Iodide-carbons	CH_3Br	CF_3Br	CF_3I	CH_3I
Molecular structure				
GWP	5 (IPCC, 2007)	5.800 (Drage et al, 2005)	< 5 (Kieffel, 2014)	0.03 (McTague, 2000)
Boiling point	3.4 (Pubchem n.d.)	-58 (Pubchem n.d.)	-22.5 (Beroual, 2017)	42.5 (Pubchem n.d.)
Toxicity	n.a.	n.a.	Mutagenic (Romero et al, 2017)	691 ppm/4h (ThermoFisher, 2010)
Flammability	No (Pubchem n.d.)	No (Pubchem n.d.)	No (Pubchem n.d.)	No (Pubchem n.d.)
Dielectric strength	0.29 (Berger, 1998)	0.54 (Berger, 1998)	1.3 (Chen et al, 2019)	1.2 (Berger, 1998)

Table C.2: Gas mixture characteristics of promising gases

C_4F_7N Mixtures	C_4F_7N / N_2 (80% / 20%)	C_4F_7N / CO_2 (80% / 20%)	C_4F_7N / O_2 / CO_2 (6% / 5% / 89%)	C_4F_7N / O_2 / CO_2 (3.5% / 13% / 83.5%)
Molecular structure				
GWP	1334 (Pan et al. 2020)	1104 (Pan et al, 2020)	614 Calculation	394 Calculation
Boiling point	-25 to -20 (Seeger et al, 2017)	-25 to -10 (Seeger et al, 2017)	-25 (Smeets et al, 2022)	-30 (Smeets et al, 2022)
Toxicity	Non-toxic (Pan et al, 2020)	120.000 (Kieffel, 2014)	12.000 (Romero et al, 2017)	12.000 (Romero et al, 2017)
Flammability	No (Pan et al, 2020)	No (3M, 2017)	No (3M, 2017)	No (3M, 2017)
Dielectric strength	n.a.	0.87-0.96 (Kieffel, 2014)	0.96 (Smeets et al, 2023)	0.87 (Smeets et al, 2023)
$C_5F_{10}O$ Mixtures	$C_5F_{10}O$ / Air (5%/95%)	$C_5F_{10}O$ / O_2 / CO_2 (6% / 12% / 82%)		
Molecular structure				
GWP	0.6 (Izagirre, 2022)	< 1 (Seegers et al, 2017)		
Boiling point	0 (Owens et al, 2020)	-5 to +5 (Seegers et al., 2017)		
Toxicity	n.a.	200.000 (Smeets et al, 2023)		
Flammability	n.a.	n.a.		
Dielectric strength	0.81 (Preve et al, 2015)	0.75-0.86 (Smeets et al, 2023)		
$C_2H_2F_4$ Mixtures	$C_2H_2F_4$ / N_2 (80%/20%)	$C_2H_2F_4$ / Air (70%/30%)		
Molecular structure				
GWP	1214 Calculation	1159 Calculation		
Boiling point	< -26 (Ullah et al., 2018)	< -26 (Ullah et al., 2018)		
Toxicity	Non-toxic (Ullah et al, 2018)	Non-toxic (Ullah et al, 2018)		
Flammability	No (Ullah et al, 2018)	No (Ullah et al, 2018)		
Dielectric strength	0.85-0.90 (Ullah et al, 2018)	n.a.		

Appendix D. Figures and tables for environmental impact comparison

Table D1: Raw materials for a 145 kV electrical switchgear (Hyundai Electric, 2023)

Materials	SF_6 [kg]	C_4F_7N [kg]	Percentage [%]
Aluminum	1820	1915	61
Steel	1000	1050	33
Copper	65	68	2
Epoxy	120	125	4
Total weight	3005	3158	100

Table D2: Raw materials for a 145 kV electrical switchgear (General Electric and Hitachi Energy, 2023)

Materials	SF_6 [kg]	C_4F_7N [kg]	Vacuum [kg]	Percentage [%]
Aluminum	1588	1658	2744	68
Steel	460	478	795	20
Copper	29	29	50	1
Epoxy	263	279	454	11
Total weight	2340	2444	4043	100

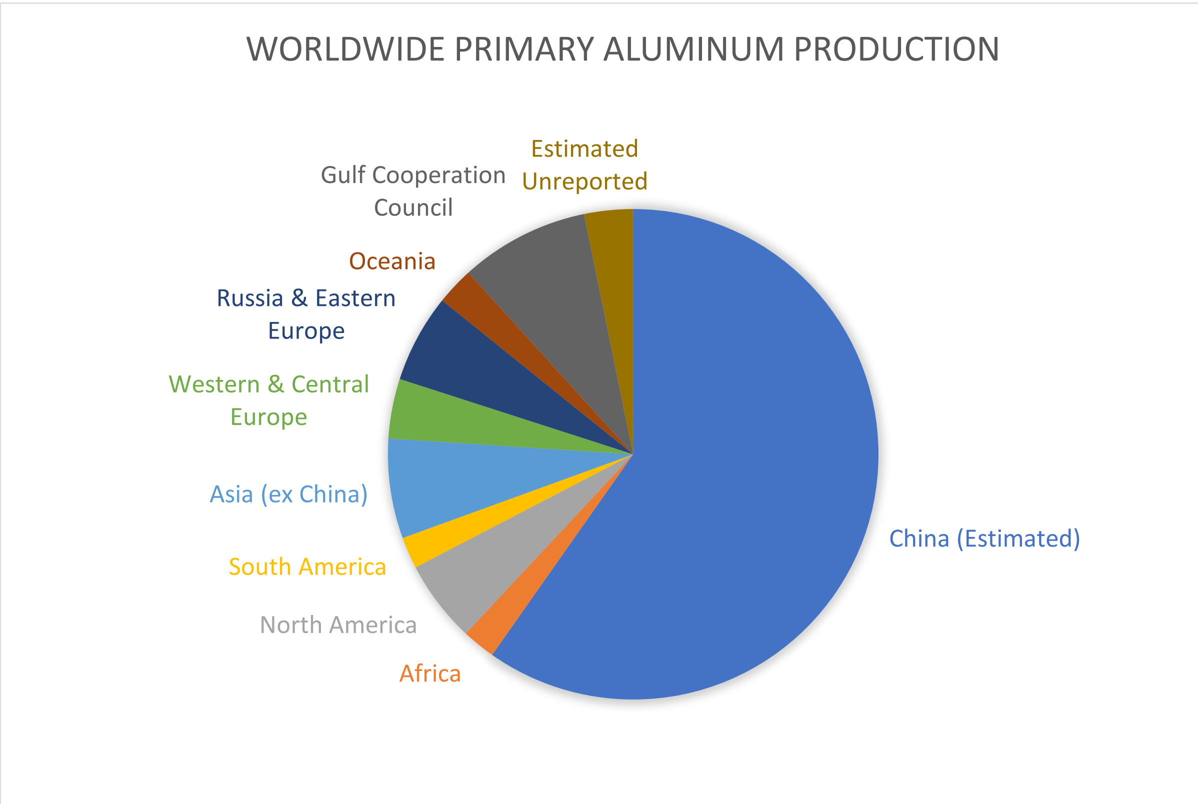


Figure D1. Primary worldwide aluminum production for November 2024 as adopted from International Aluminium Institute (2024).

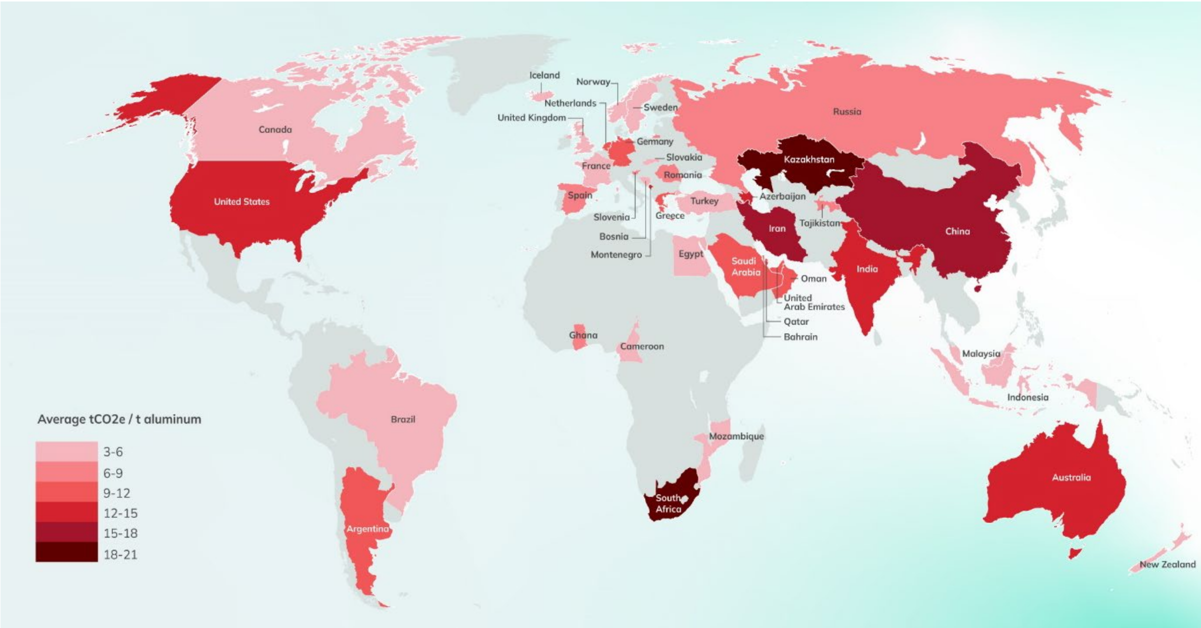


Figure D2. Average aluminum CO2 equivalent emissions as adopted by Berker (2022)

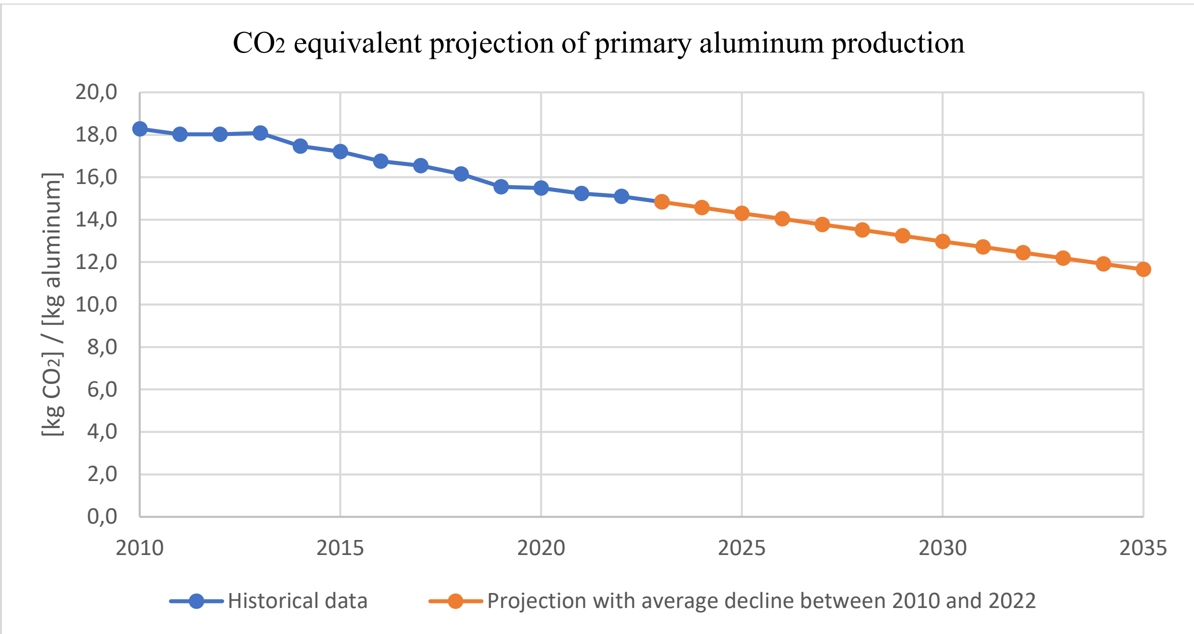


Figure D3. projection of primary aluminum production based on historical data published by the International Energy Agency.

Table D3: CO2 equivalent emittance for manufacturing of a 145kV electrical switchgear with estimated aluminum emittance reduction in 2035.

Materials	[Kg CO_2] / [Kg material]	SF_6 [kg CO_2]	C_4F_7N [kg CO_2]	Vacuum [kg CO_2]
Aluminum	11,7	22539	25545	33305
Steel	1,4	1112	1260	2190
Copper	4,1	209	237	417
Epoxy	4,8	1097	1243	901
Total weight	-	24957	28285	36812

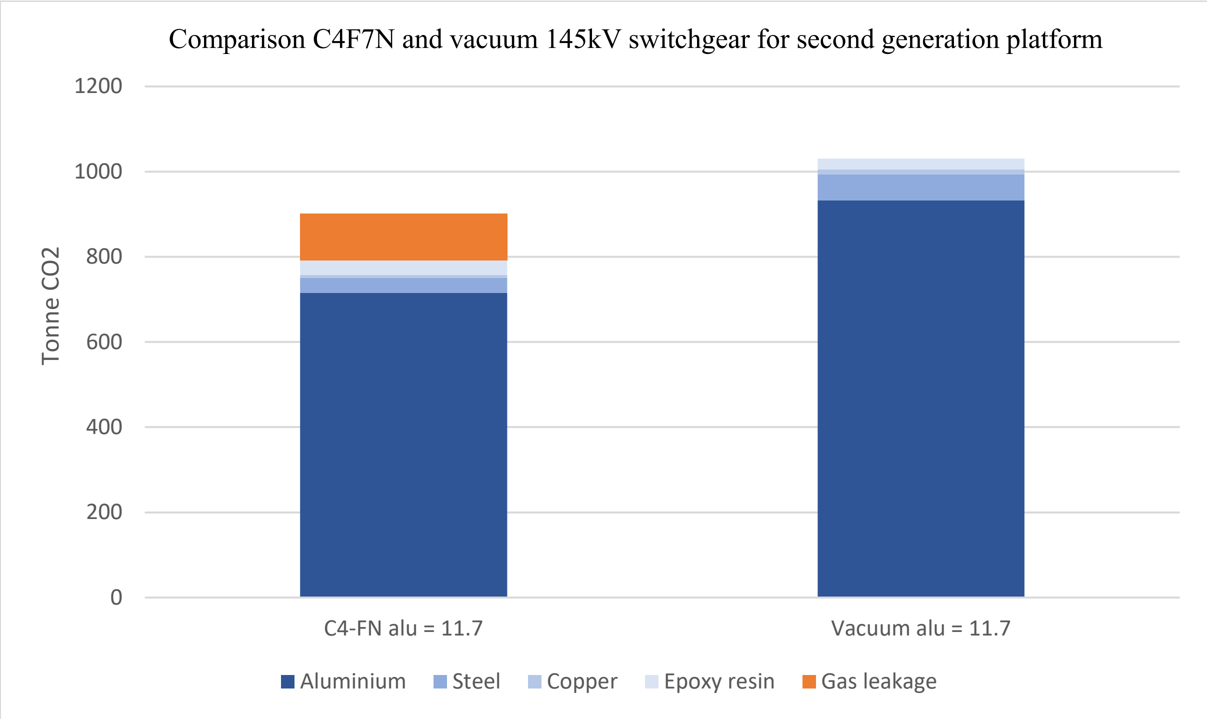


Figure D4. Comparison of C_4F_7N and vacuum 145kV switchgear with an aluminum intensity of 11.7

Appendix E. Transcription of interviews

This appendix presents the transcription of the semi-structured interviews. A total of four interviews were performed to better understand GIS technology, market dynamics, and stakeholder interactions. The job functions of the participants are outlined below.

Participant I: Offshore Development Advisor at TenneT
Participant II: Offshore GIS installation Specialist at TenneT
Participant III: Project Developer of the TenneT Innovation Track
Participant IV: Sustainability Program Leader of General Electric

Interview participant I

Timo: Welcome, my name is Timo, and I am currently working on my master's thesis for my study in Complex Systems Engineering at TU Delft. My research addresses the use of SF6 gases and finding alternatives in GIS installations. For this, I will conduct an MCDA, a method in which you can compare different alternatives. As an introduction, I am defining the scope of TenneT. I am interested in stakeholders and why TenneT operates the way it does within the 2GW program. The sub-question I want to address in this chapter is: what is the decision context within which TenneT operates in the offshore wind industry? My first question addresses the system context and scope of TenneT. What factors play a role in determining the scope of an offshore wind project?

Participant: First of all, it has to do with our designation as the grid operator at sea. In the Netherlands, Rijkswaterstaat determines where the wind farms will be located. Then a permit is granted by the Netherlands Enterprise Agency (RVO), which subsequently issues a tender. The specifications for that tender are drawn up by the ministry. So, multiple parties are involved. Eventually, an area at sea is designated where wind turbines must be placed. Companies can bid to install them there. The market situation plays a role, but generally, it generates money for the state as parties bid for these plots. Regarding the connection of the wind farm: the realization of this is the responsibility of TenneT. We already know in advance where the plots will be located. We are also involved in the permitting process and consult with Rijkswaterstaat about how it should look exactly. Based on the size of the wind farm and the distance to the coast, we determine which technology fits best: alternating current (AC) or direct current (DC). For the first projects, such as Hollandse Kust and Borssele, we opted for AC platforms because these wind farms are relatively close to the coast. The distance to the landing point plays a big role. For wind farms further out at sea, like those in the future, we use a 2 gigawatt (GW) DC connection. For projects that are further away, you have to switch to DC from about 80 to 100 km from the coast. This is because AC is no longer efficient over longer distances, partly due to the lack of infrastructure in areas such as Den Helder. That's why we choose to make the landing at places like Maasvlakte or Borssele.

Timo: What do you see as the main challenges and opportunities of the 2GW project?

Participant: There are quite a few challenges, especially since a 2 GW platform as we want to build now has never been done before. But we do believe it's feasible. The opportunity this provides is that we create a new standard that is more widely adopted than just by TenneT. This doesn't have direct financial benefits for us, as we don't make money from these platforms themselves. But if this becomes the market standard, the entire supply chain can focus on it, which might bring more competition and lower costs for us. In the long term, it can be cost-saving.

Timo: What decision-making processes are applicable within the 2 GW project? Does it start with the tender process?

Participant: No, it actually doesn't start with the tender process. It starts with VAWOZ (Offshore Wind Landing Connections). In the Netherlands, we had VAWOZ 2021 and now we are working on VAWOZ 2030. This determines how many wind farms are needed to meet the climate goals and where they will roughly be located at sea. This is established before the exact cable routes are determined. For example, we already know that a cable from a wind farm must run to Eemshaven. After VAWOZ, a series of projects that are included in the development framework follow. This framework serves as the official assignment for TenneT to build a platform. The tenders are important, but mainly to determine which party will develop the wind farm. We have already started our preparations before the tender is concluded. Once the tender results are known, we know which party will be our counterpart. While the basic design of the platform is already fixed, there are a number of technical details that need to be aligned with the winning party. For example, how the cables from the seabed are connected to the platform. Here, our systems must seamlessly connect to prevent any disruptions. For TenneT itself, the tender process is mainly important to know who the wind farm developer will be, since we are already sure of our role as the grid operator at sea. Competition with other TSOs does not play a role here.

Timo: The construction of platforms and wind farms is done by different parties. How do these tenders differ from each other?

Participant: For building those platforms, we have framework contracts, just like for stations on land. Once we have certainty through the development framework, we can essentially give the order and order the platforms.

Timo: TenneT works with project clusters and portfolios. How are these precisely arranged?

Participant: I'm actually an outsider, as I work in offshore development, and I sometimes find it quite complex. I do understand the structure itself: you have a platform that can fully focus on the construction of that platform, which is an important and expensive part of the project. Those platforms are often built far away, like in Singapore, including all the components. Then they are shipped, and that's quite complex. The platforms, cables, and converters are all complex parts. Additionally, the clusters or portfolios are arranged per contract, which is handy because you can then cooperate well with that contractor, even across the national borders of the Netherlands and Germany.

Timo: I have created a visualization of the 2 GW project, where I found an image showing the General Electric Seatrium Consortium (GSC) in red and Petrofac Hitachi (PHE) in blue. Why was it chosen to split this into two parties in the Netherlands?

Participant: In total, we have three parties in our framework contracts: Siemens, General Electric (in Germany with a different partner than Seatrium), and Petrofac Hitachi. Siemens mainly focuses on projects in Germany. For each cluster, we have specific allocations like Doordewind for the Eemshaven cluster. We also have clusters like Borssele and Maasvlakte, and those clusters are fully responsible for delivering the entire project, including the charging station and the cable. However, those clusters must also ensure everything works and remain responsible until the platform is operational.

Timo: Is it already known where the onshore stations will be located exactly?

Participant: Sometimes, but not always. Those locations must be determined and built in time, which is the responsibility of the cluster. Each cluster has a strong location orientation, both onshore and offshore, which often makes coordination complex. Clusters have to coordinate both the platforms and the cables well, which doesn't always go smoothly.

Timo: Does TenneT take measures to improve collaboration between clusters?

Participant: Yes, it falls within one department, so there is certainly cooperation. We have NT meetings and other coordination meetings, but it doesn't always go smoothly. Everyone does their best, but the cluster approach offers advantages, such as maintaining standards within projects.

Timo: How does decision-making differ between TenneT in Germany and the Netherlands for offshore wind projects?

Participant: The decision-making is officially the same, but there are differences. In Germany, they work with an FEP (Flächenentwicklungsplan), which is comparable to our development framework. In the Netherlands, it's more of an investment report that is updated every few years, while in Germany, everything is combined. This leads to some differences in decision-making.

Timo: Are measures taken to promote collaboration between the LPO departments of TenneT Germany and the Netherlands?

Participant: Saskia is the main responsible for both the LPO in Germany and the Netherlands. There are quarterly meetings to coordinate, but the offshore development department is often externally focused, which can cause complexity in coordination.

Timo: Who do you think are the main stakeholders in offshore wind projects?

Participant: Primarily the Ministry of Climate and Green Growth (KGG). They determine the roadmap for climate ambitions. Then you have the offshore wind farm developers, such as Vattenfall, RWE, Eneco, Shell, and BP. For them, it's mainly about the business case, which needs to remain attractive.

Timo: Are there other parties outside these wind farm developers who could take on this work?

Participant: No, these are the main parties, but they come from different corners. For example, Shell has a background in offshore, while Vattenfall and RWE expand their expertise from onshore wind turbines to offshore.

Timo: The market for high-voltage platforms seems largely in the hands of General Electric, Hitachi, and Siemens?

Participant: That's right. Globally, they are the major players in high-voltage equipment. The market is quite limited, and for safety reasons, we are not allowed to just buy Chinese products due to regulations concerning critical infrastructure.

Timo: Why are certain projects, like IJmuiden Ver Alpha and Beta, carried out by different parties?

Participant: This probably has to do with the capacity of suppliers. One supplier can only work on one platform at a time. By dividing the projects, you ensure they don't become overloaded and can meet the deadlines.

Timo: What impact does European legislation have on offshore projects, like the new F-gas regulation?

Participant: For electrical engineering, we have to comply with increasingly strict rules. The Net Zero regulation comes in 2026 and will impose stricter requirements for sustainable purchasing within the EU. This will also affect our platforms and other sustainable installations.

Timo: What does the future of offshore wind energy look like for TenneT, and what role does innovation play in it?

Participant: Offshore wind is essential, especially because onshore turbines are becoming larger and less suitable for locations close to buildings. The Netherlands has ambitious goals, such as achieving 32 GW of capacity by 2032. So, we also need to electrify and modernize the grids to efficiently use all that energy.

Timo: Does TenneT expect the tender procedures to become more problematic in the future?

Participant: Yes, definitely. We already see that splitting tenders into smaller projects of 1 GW is necessary to limit the risk for investors. Larger projects pose too great a financial risk, causing investors to drop out.

Timo: Could TenneT play a role in deploying hydrogen for the industry?

Participant: Certainly, hydrogen is a good way to store energy and use it later. You can deploy it directly in a factory or use it to drive a generator. Both options are possible. So, it can serve as reserve capacity or directly feed the industry, depending on what you want to achieve.

Timo: How does TenneT handle uncertainties and risks in offshore wind projects? Is there a specific department within TenneT for this?

Participant: Yes, that falls under project risk management. They manage the risks per project.

Timo: Is that a general approach or is it organized per cluster?

Participant: There is a specific department within Business Guidance that oversees this. They have their own risk project managers, and each cluster has its own risk manager. For some projects, like Link, there is a separate risk manager. For example, Nederwiek 3 has its own manager, separate from the one overseeing the whole.

Timo: Then I have one last question more specifically focused on the GIS installations. Do you know if the GIS installations used by different parties differ from each other?

Participant: That's a good question. I suspect so, but I'm not entirely sure. It seems likely that there are differences, because we deal with different technical qualifications (TQs). From different contracts, you always get feedback. For example, Hitachi Energy focuses on different points than GE. There almost certainly are two different installations.

Timo: Yes exactly, I will also discuss this with Participant II, who probably knows more about this.

Participant: Yes, he has a good understanding of the GIS installations.

Timo: Thank you for your cooperation in this interview.

Participant: You're welcome, I'm curious about the results.

Interview participant II

Timo: I am currently outlining the context of the 2 Gigawatt project. And there, I discussed several topics with Participant I. However, I still have some questions specifically about the GIS installation. So what I've found is that the cables from the wind turbines come in at 66 kilovolts and then are converted to 525 kV if I understand correctly.

Participant: Yes, that's correct, converted to direct current.

Timo: Is a GIS Installation needed for 525 kV, or is 66 kV sufficient?

Participant: It is currently suitable for up to 145 kV.

Timo: OK. And how does that work exactly? Is a 66 kV GIS installation adequate?

Participant: Yes. In principle, we only need 72 kV. Using 66 kV falls within the class up to 72.5 kV. However, we require some features that are only available on the 145 kV installation, which is just a bit larger.

Timo: So, you should base it on the incoming current, not the 525 kV?

Participant: Correct, it's really just 66 kV.

Timo: Are multiple GIS installations needed side by side, or is one sufficient?

Participant: We have two, two distinct installations.

Timo: And why are two installations necessary?

Participant: Well, it's mainly for risk mitigation.

Timo: The busbars essentially ensure that if one fails, you can rely on the other. What is the purpose of the second GIS installation?

Participant: Exactly. The second installation does precisely the same thing. It's essentially a duplicate, and they are also interconnected.

Timo: So, in the current system setup, you would have two 66 kV GIS installations standing next to each other?

Participant: Yes, that's correct.

Timo: That opens up a lot of possibilities. Until now, I was actually focusing entirely on all installations in the market that go up to 400kV. But this means that options for 145kV are also viable, or even 70kV.

Participant: Yes, let me just check. I'll share my screen; I have an image. Currently, we have this setup. Here below, we have the two GIS installations. And one GIS installation feeds two transformers. So, in case a busbar fails, you actually only lose 1/8 of the power.

Timo: 1/8, meaning there are four busbars on each side.

Participant: Yes, both sides have four busbars.

Timo: Interesting. Then I have another question about the cable from the offshore station to the mainland. Do you know why a 525 kV HVDC cable was chosen?

Participant: That's just the standard in electrical engineering. You typically have two options, 325 kV which is common, and above that, you quickly move to 525 kV. It reflects where the market is currently heading, and suppliers strive to standardize it.

Timo: Which suppliers are involved in this case?

Participant: The cable must be suitable for 525 kV, but all components of the installation on the platform as well.

Participant: And therefore, it's best to always opt for those standard values.

Timo: OK, yes. Just looking at a few more questions. We have the GE installation on our platform (GSC); do you know if the GIS installations from Hitachi and Siemens occupy about the same space?

Participant: Yes. Siemens's model is slightly larger because it uses a different insulating gas, as you probably know. However, they are relatively comparable; the difference isn't substantial.

Timo: Yes, okay, so a GIS installation from different companies could feasibly be implemented on the same platform without one being significantly larger than another.

Participant: I expect that you should be able to work that out.

Timo: Hitachi and GE are now focusing on fluoroketones, do you know if they are exploring other options, or are they solely focused on this option?

Participant: No, I know GE is also exploring clean air solutions (vacuum), but that's not officially confirmed; I heard it through the grapevine.

Participant: Fluoroketones might also prove challenging to use because they still have a somewhat elevated Global Warming Potential (GWP). It's very much a wait-and-see situation to see what the European Union decides to do about it.

Participant: And then there are other issues with fluoroketones; they are F-gases and fall under the PFAS category. The production of these gases has already completely stopped in Europe. This also concerns the Novec gas from 3M. Currently, all this gas must come from China.

Timo: Yes, exactly.

Participant: It's not expected that China will change its export policy soon, but there's always a risk. If China decides to stop supplying, it will become problematic.

Timo: Yes. And you also mentioned Clean Air, which Siemens is working on with vacuum technology. Do they have a variety of options available?

Participant: They essentially have two options: SF6 or Clean Air. They are increasingly promoting Clean Air. It hasn't yet been used in high voltage, but it is being used in medium voltage. They have already discontinued SF6 installations in some areas.

Timo: Yes, so if they have a GIS installation that could work at 145 kV, it could theoretically be installed on offshore platforms.

Participant: Yes.

Timo: What exactly is the difference between medium voltage and high voltage?

Participant: In the Netherlands, anything above 50 KV is considered high voltage. Between 6 kV and 50 kV is medium voltage.

Timo: Yes, exactly.

Participant: Siemens is currently between 10 and 20 kV, which you'll find in every neighborhood or street. They are actively pushing Clean Air in this range.

Timo: Regarding contractual agreements on the platforms, what's the situation with changing GIS installations? For instance, could another installation be set up now, and until when would that be allowed?

Participant: We have finalized the basic design for this installation, and production is set to start early next year. So, at this point, we are essentially locked into this type of installation.

Timo: So, if there could be an installation that indeed does not use F-gases, could it still be installed?

Participant: I don't expect that for these five projects anymore. That would be something to consider for platforms after 2032.

Timo: For the five platforms currently being installed, are they using fluoroketones or SF6?

Participant: We've stipulated in our conditions that we have a strong preference and are obligated to start using alternative gases.

Timo: Are there other providers besides GE, Hitachi, and Siemens who could realize a platform or set up a GIS installation?

Participant: Yes, for GIS installations, Hyundai.

Timo: Online, I found Hyundai Electric and LS Electric.

Participant: From memory, Mitsubishi also builds GIS installations. And then there are several Chinese suppliers.

Timo: Yes. Clear. And do you know why GE, Hitachi, and Siemens were chosen for the 2GW program?

Participant: Yes, they are the only three Western suppliers at the moment.

Timo: Are there other potential parties that will enter the market in the coming years?

Participant: Well, we have another project running in Germany, that is BolWin6. We're doing that with a Chinese supplier. That project is already underway, but it's politically a bit more sensitive.

Timo: Yes, exactly.

Participant: There's a real concern that if you place 10 gigawatts at sea built by a Chinese manufacturer, they could potentially shut it down, which would quickly lead us back to European suppliers.

Timo: Yes, and is that more about the supply of the gas or the installation itself?

Participant: The installations from Chinese parties are also good, but it's mainly politically sensitive. And it's ultimately politics that make the decision.

Timo: I have a few more questions about the Multi-Criteria Analysis. I have now set up the following criteria with six main themes. Do you agree with these main themes**?** or do you think there is a theme missing?

Participant: I would include the criteria of boiling point, as the gas has to maintain in a gaseous state

Timo: Yes, that's a good suggestion, which would fall under technical requirements.

Timo: what is the pressure for SF6 installations?

Participant: Around 6, depending on the installation, between 5 and 8 bar.

Timo: Are there themes or criteria among those that are not really relevant now?

Participant: Maybe the stability of the gas over the long term, and the economic criteria.

Participant: Then your criteria seem complete, I think.

Timo: Now I have actually found these alternatives. With the requirements on the y-axis and the alternatives on the x-axis, divided into groups. I want to test these later based on all those criteria. But first, I want to make a selection in the alternatives; otherwise, there will be too many.

Participant: I noticed that too. You basically have two alternatives on the market, or three alternatives. You have the fluoroketones where there is quite a bit of development, where you can also get installations.

Timo: Yes.

Participant: Then you have fluoronitriles. I know that *** used them for a while in medium voltage installations. They conducted several tests with them, but I know that *** has now also backed away from that.

Timo: Do you know what the reason was that they stopped with that?

Participant: I couldn't say for sure.

Timo: Then I will do some more research on that.

Participant: I have another comment about something that struck me. Do you also use vacuum?

Timo: Yes. Yes.

Participant: Then you probably mean the Siemens installations, I expect. They function a bit differently because the GIS itself is actually under overpressure. They've actually gone back to using technical air under overpressure, I believe it's really around 10 bar that's in it. And the switching itself is often done with a vacuum switch. So they use a combination of fairly high air pressure, often for switching.

Timo: Yes. Yes. And what gas is in there then?

Participant: They call it technical air, so it's actually just a mixture of CO_2 and nitrogen. I believe there's also a small percentage of oxygen in it.

Timo: With a first selection, I want to reduce the 35 options listed here to about 10, I think. As I've planned, I want to first select based on GWP, then toxicity, then flammability, then ODP, and then on dielectric strength. Would you recommend these parts too?

Participant: I agree with your criteria, but I would include boiling point between GWP and toxicity.

Timo: Regarding boiling point, if a gas has a boiling point of for example 10 degrees, then I won't include it because then it's unsuitable.

Participant: Yes, or you must use it in a mixture.

Timo: Yes, exactly. I've also seen that, for example with fluoroketones and a pure 3M™ Novec™ 5110 (C5F10O). Those are not suitable on their own because of their boiling point, so they are then eliminated. But a mix of them can be suitable.

Participant: Yes. In the Netherlands, we don't use those in practice, but we even sometimes make mixtures with SF_6.

Timo: Yes, yes exactly.

Participant: With CO_2 to lower the boiling point.

Timo: Yes. But I thought that if they also do not fall within those temperature limits with a mix, they are unsuitable for an installation. Is that correct?

Participant: Yes, that's correct. It must always remain in gas form.

Timo: Yes, yes. Exactly. And that temperature range, there was some discussion about that yesterday. You set it at minus 15 to plus 40 degrees, but I found in many articles that minus 30 degrees was assumed.

Participant: That depends on where you're going to apply it.

Timo: Of course, that depends on the environment. It's not likely to reach minus 30 degrees in the Netherlands.

Participant: Look, on a platform, both on land and offshore, it will never be minus 30 degrees. At sea, it won't even freeze.

Timo: Yes.

Participant: So if you maintain minus 15 degrees, you're already on the safe side.

Timo: Yes.

Participant: But if you're really going to apply it in Russia, then minus 30 degrees would be useful.

Timo: Yes, okay. That's why I thought it was important to be able to eliminate some gases based on that.

Participant: If there are still many options left, you can then look at other criteria.

Timo: Yes, as I have it set up now, you see that some gases already fall out based on their boiling point.

Participant: Yes, yes. I would personally select almost first on GWP.

Timo: Okay.

Participant: TenneT is looking more and more at that.

Timo: From the GWP perspective?

Participant: Yes.

Timo: And what threshold values do they set?

Participant: According to the new European guideline, different GWP values are mentioned.

Timo: Yes, that's right, I think there are three.

Participant: Yes, there are three categories: one under 1, a second from 1 to 1000, and the third from 1000 and higher.

Timo: Yes, so would you stick to these categories?

Participant: Yes, that's right. Above 1000, you really wouldn't want to use anymore. So I would set the limit at 1000 and look for something that falls below that so that it is still applicable.

Timo: Okay, so you would say: first select on GWP and exclude everything above 1000. Then look at toxicity, then boiling point, and then flammability.

Participant: Yes, yes, exactly.

Timo: Are there any other criteria where you say: if a gas has that, it immediately falls off?

Participant: Yes, it must remain a gas, that is very important.

Timo: Yes, so that it remains in gas form.

Participant: Exactly.

Timo: Okay, then I will further develop this in the table. I indeed think that if I set the limit at 1000, I can well substantiate why I made that choice.

Participant: Definitely. If you keep that limit of 1000, you can immediately explain why that is a suitable threshold.

Timo: Do you have any further questions about something I'm working on for my research?

Participant: No, I think you're quite on track, as I see it.

Timo: Yes, well great, thanks for the interview.

Participant: Great. If there is anything, send a message or call.

Timo: Thank you, have a great vacation.

Participant: thank you.

Interview participant III

Timo: First up is a figure (Figure 3.1.3). These are the initial results from my research into the European regulation concerning F-gases. In this figure, three different markets are identified. On the left, you see the voltages for the electrical switchgear, covering up to 145 kV. These installations are already operational on platforms and are permitted to use SF6 until 2028 since there's no limit on the GWP. Next, there's a two-year transition period during which using a GWP between 1 and 1000 is allowed, provided there is a supplier, such as Siemens currently. If a second supplier emerges during the transition period (market 2), we will immediately switch to market 3. Market 3 is essentially the definitive market that mandates a GWP under 1.

Participant: Yes.

Timo: Initially, I assumed that market 2 had no expiry date, meaning it could continue indefinitely until a second supplier appeared. However, after reviewing the regulations again, I found that market 2 has a maximum transition period of two years, ending in 2030 for 145kV setups. From then on, Siemens will be the sole provider, as things stand. When are the second and third generations scheduled for TenneT?

Participant: The second-generation platform begins with projects post-2032. So, in 2032, we still have Baldwin 5 in Germany and DoorDeWind 1 in the Netherlands, which are essentially the last of the first generation. For the second generation in Germany, we have LanWin7, which will transition to 132 kV. That's where we're targeting the second-generation platforms. In the Netherlands, we also have DoorDeWind 2 afterward, which will still be first generation and will need reconfirmation from the Ministry of Economic Affairs.

Timo: I'd also like to show the next figure (Table 6.2.1).

Participant: Perhaps we could revisit the first figure? The European Commission has indicated specific timelines. These are indeed the dates by which it is prohibited to commission switchgear. However, they also consider the tender date, i.e., the purchase date when, for example, DoorDeWind 1 and 2 were procured.

Timo: Yes.

Participant: The framework agreement hasn't occurred yet, but we proceed as if it has. Even though the operational dates aren't until 2032 and 2034. Since the purchase date preceded the regulation's implementation, proving this would mean the regulation doesn't technically apply. Hence, we should still be able to use DoorDeWind 1 and DoorDeWind 2 as solutions.

Timo: Yes, that's correct. If it was ordered before the regulation was announced, an exception applies.

Participant: Exactly, and so all future projects and everything we purchase from now on will adhere to this regulation, requiring compliance with the set standards.

Timo: Regarding the second figure (Table 6.2.1), this is how I've incorporated it. The first generation runs from 2029 to 2032, which involves the construction phase.

Participant: Yes.

*Timo***:** Regarding the third generation, I believe it runs until about 2040, or do we have an idea yet?

Participant: Actually, yes. I think it's currently projected for around 2037. That's because, in 2037, at least from Germany, we'd like to shift towards multi-vendor systems. Right now, if we build an HVDC system, it's entirely from one supplier—whether Siemens, Hitachi, or GE. But in 2037, Germany will initiate multi-vendor systems. This will mark the start of the first offshore projects that will be part of a much larger DC network. We want to ensure that not the entire network depends on a single supplier, so this is the period targeted for the transition to multi-vendor interoperability.

*Timo***:** And how should such a multi-vendor system appear, would that involve Siemens, Hitachi, and GE collaborating?

Participant: Oh yes, for example, a Hitachi platform could be connected to a Siemens charging station, right? This means that the converters and their controls should be interoperable. Currently, this is not the case.

*Timo***:** Yes.

Participant: Yes, it's entirely managed by one supplier.

Participant: There's a European program called Inter-opera addressing this. It involves the united TSOs along with market parties, assessing how to facilitate this transition. The changes needed are not solely technical but also largely political.

*Timo***:** Yes.

Participant: Yes, these parties do have a significant interest in ensuring that for TSOs, it's crucial to use multiple suppliers within a system. Conversely, the suppliers have a vested interest in ensuring that once a system is purchased, the buyers remain tied to them, blending commercial interests with politics.

*Timo***:** Yes, I understand. I have a few more questions. First off, what's the expected capacity of the wind turbines for both the second and third generations?

Participant: Yes, good question. Currently, there's no clear consensus in the wind industry. For instance, one wind turbine supplier claims they now have a 15-megawatt turbine operating at 66 kV, and they intend to continue using this model until roughly 2040 without transitioning to a larger turbine or higher voltage level. Meanwhile, other suppliers are keen on making these changes, which complicates the industry consensus on development towards 2040. There's a strong movement advocating for standardization at 15 megawatts, impacting various factors like blade length, transport and installation capabilities, foundation size, and the associated steel thickness and underwater noise during installation.

*Timo***:** Yes.

Participant: And there's currently no consensus within the industry about this.

Timo: You mentioned that one group is indeed interested in innovating to 132 kV. They are willing to take that step.

Participant: There's also a current that says, yes, we are prepared to make the move to 132 kV.

Timo: Yes. And from TenneT's perspective, what's the preferred approach?

Participant: Well, our view is you always need to consider carefully when making such decisions. Firstly, the decision doesn't rest with TenneT. It lies with the Ministry of Economic Affairs in the Netherlands and its German counterpart. To make such a decision, one must consider the Levelized Cost of Energy, assessing the most cost-effective way to integrate produced wind energy. If the market were robust, then stepping up to 132 kV would make sense, as it significantly reduces cable length requirements within wind parks.

Timo: Yes.

Participant: And looking specifically at the TenneT portion, it would represent a cost-saving for us since operating at a higher voltage level means transporting the same power but with lower currents, thus requiring fewer cables to draw that power. This means fewer connection points need to be established for linking the wind parks.

Timo: Yes, which translates to fewer switchgear installations.

Participant: Fewer J-tubes on the platforms and all the associated spatial and material savings that come with it. So, in principle, we are in favor.

Timo: Yes. Because the number of switchgear installations was also reduced from 40 to 24 for a 132kV system.

Participant: Yes, and considering those 24 connections, when I account for them, we could potentially establish even more connection points at 132 kV for clients beyond just wind parks, perhaps even for an electrolyzer. This would enable the conversion of wind-generated energy into hydrogen directly at sea.

Timo: Yes, yes.

Participant: And also, when considering applications for selection, if you need to connect other types of clients who also require significant connection capacity, higher voltages offer advantages. So, moving to an offshore hub where an electrolyzer needs to be connected makes sense from our perspective; it's logical to switch to 132kV.

Timo: So to sum it up, the primary advantages of 132 kV are fewer cables, less material, and thus lower costs.

Participant: Yes, fewer assets.

Participant: Yes, and the space that becomes available because you have significantly fewer switchgears and cables on and around your platform also allows for the connection of other clients on the same platform.

*Timo***:** Yes. What then is the biggest barrier to 132 kV? Is it that the market does not want to produce turbines above 15 megawatts, or are there other barriers?

Participant: No, that's the biggest barrier right now. Not all turbine manufacturers are performing well at the moment, so they're not all investing in new generations of turbines.

*Timo***:** Yes.

Participant: Offshore wind developers, the operators of these parks, are still generally in favor of switching from 66 kV to 132 kV, unless it causes supply chain limitations. Currently, that's the situation—if we were to make the switch to 132 kV now, for the initial projects, there would be fewer turbine suppliers available, leading to bottlenecks in our supply chain.

*Timo***:** Yes, another question about vacuum switchgear. Those are currently either C4F7N or SF6 variants from other parties. If you switch from C4F7N or SF6 to vacuum, the GIS space required becomes larger. If you then move to 132 kV, this reduces to 24 vacuum switchgear installations, which is roughly the same total size as 40 SF6 or C4F7N installations. Does this play a role in Tennet's decision to move to 132kV?

Participant: I'll need to check, but I believe that a vacuum field is slightly larger than if the same field were configured at 66 kV. However, I think the size difference is manageable.

*Timo***:** I have previously made an overview of this.

Participant: Yes, you know how we designed our two-gigawatt platforms? We have a standard design, and we've stated that the GIS spaces are based on this standard. These spaces are the same size across all three suppliers, so they're designed to be independent of the supplier. That means any solution fits in the GIS space, based on 66 kV, and this is based on a GIS with 40 fields. Looking at Siemens' guide and their Clean Air technology, it's 20 cm wider per field than a GIS operating on SF6 gas. The width of 1 m for Siemens' GIS with Clean Air is still narrower than, for example, Hitachi's SF6-free solution at 1.2 m, so if the GIS from Hitachi fits with a width of 1.2 m, then that's the widest GIS we have, and the size of the spaces is based on that.

*Timo***:** Yes, but the depth of the Siemens installation is significantly larger.

Participant: Yes, the depth, well, that means our GIS space is currently based on that 5.5 m from Siemens.

*Timo***:** I wonder if the current GIS space, set at a depth of 4 m, would fit Siemens' which is 5.50 m?

Participant: I think it would, because we've created a universal design that's supplier-independent. We've made layouts for the platforms that include GIS space, and the design of this space is based on input from all three GIS suppliers.

Timo: Okay.

Participant: So, you see, the space is designed to accommodate the widest, tallest, and deepest dimensions available.

Timo: So essentially, the platforms in Germany that Siemens is implementing have the same GIS space size as those in the Netherlands.

Participant: Yes, we've provided a standard design as Tennet, which includes a specific space for the GIS rooms. We've given the same space to all three suppliers. I'm not sure if they've deviated from that in their specific designs, but in principle, we've set the size of these spaces.

Timo: Okay. So those are the 2OC platforms in Germany from Siemens that currently have 40 vacuum installations.

Participant: Yes, well, those are things we are now going to investigate with the suppliers, but in principle, we're assuming that. Yes, that GIS, we're essentially going to use the same GIS products in the next generation because Hitachi and General Electric also have no plans, at least as far as we know, to switch to a vacuum solution.

Timo: Yes. No, I've spoken with someone at General Electric who also looks at sustainability and the upcoming generations, and they've indicated that they're focusing on the ecodesign directive. It's due out in April this year. They'll likely be evaluating the emissions of the entire product to demonstrate that the C4F7N variant is more sustainable than the vacuum across the entire lifecycle process.

Participant: Correct, I've heard those stories from General Electric as well. From what I understand about the ecodesign guideline at the moment, it does not apply to Switchgear, and that's what the European Commission has responded to inquiries from the European Parliament. But whether there will be changes to include Switchgear in the ecodesign directive, I'm not sure, but now, the path that General Electric wants to take doesn't seem feasible.

Timo: Yes.

Participant: So, I know they are indeed lobbying for that, and they are trying to get some sort of exemption through that route. But whether that's likely to succeed, I don't know.

Timo: Yes, we'll see. Thanks for all the responses.

Participant: Okay, good luck with the completion of your study.

Timo: Thank you. I'll send it to you once I've finished.

Participant: Alright! Bye.

Timo: Bye.

Interview participant IV

Timo: Dear participant, thank you for your time. My first question follows from Regulation (EU) 2024/573, there is a transition period of two years for switchgear up to and above 145kV. During this period, GE's alternative, known as G3 (Green Gas for Grid), which has a GWP below 1000, is permitted. However, after this period, the operation of this switchgear will no longer be allowed. How is your company handling this, and do you anticipate any amendments to this regulation or to Directive 2009/125/EC?

Participant: Thank you for the questions, Timo. Let's start with the Directive 2009/125/EC. It's important to note that this directive has been replaced by the ECO Design for Sustainable Products Regulation (ESPR), which took effect in 2024. This new regulation emphasizes a full lifecycle assessment of products to evaluate their overall environmental impact, shifting our focus significantly.

Timo: Can you elaborate on how this new regulation affects the inclusion of switchgears in these assessments?

Participant: Absolutely. The list of products subject to the new assessment will be published later this year, and we are particularly interested to see whether switchgears are included. We expect they will be because it would continue the logical approach previously established by the government in related regulations. This integration ensures that the adoption of new technologies for switchgears is justified through regulations like EU 2024/573, linking directly to the new ECO design principles.

Timo: With these changes, how does your company view the future of switchgear technology under the new regulatory framework?

Participant: We see it as an opportunity to further align our products with environmental goals. The new framework requires that we consider not only the type of gases used, such as our G3 technology but also the overall design and materials used in our products. For instance, while our G3 gas significantly reduces the environmental impact compared to traditional SF6, it accounts for just about 1% of our equipment's total environmental impact when evaluated under the lifecycle assessment criteria. This holistic approach is something we are preparing for actively, as it will allow us to demonstrate the comprehensive benefits of our technology.

Timo: Given the upcoming changes with Regulation (EU) 2024/573, which will disallow the use of switchgear with a GWP above 1, how is your company adapting since the G3 option will no longer be permissible?

Participant: Our strategy is very much aligned with the ECO design initiative. The regulation outlines a transition to more sustainable practices, and while it presents challenges, it also aligns with our ongoing efforts to improve our lifecycle assessments. By 2030, we aim to fully validate our designs as sustainable through detailed assessments that demonstrate their lower environmental impact compared to alternatives. This forward-looking approach ensures that we remain compliant and competitive in a rapidly evolving regulatory landscape.

Timo: So, as General Electric, are you looking to adapt to the ECO-design framework, or are you focusing on possible adaptations to the Regulations EU 2024/573?

Participant: Our focus is primarily on aligning with the ECO-design framework. We believe that our products, backed by robust data, will stand out for their sustainability in the marketplace.

Timo: Do you know if Hitachi is employing a similar strategy for transitioning away from SF6, possibly maintaining their use of C4F7N technology?

Participant: From what I understand, Hitachi's approach is similar to ours. They are not pursuing a complete transition away from F-gases for similar reasons, recognizing that the overall lifecycle assessment often favors the continued use of certain F-gases due to their lesser environmental impact compared to other materials that might be used otherwise. This perspective is shared by several major industry players, suggesting a common view that while alternatives exist, their practical application may be limited by technological and environmental factors.

Timo: If vacuum switchgear technology could match the lifecycle emissions of your G3 option, particularly by reducing manufacturing emissions, what would be your company's next steps?

Participant: It's difficult to predict specific company strategies, but generally, the decision would be driven by data. If vacuum technology and our G3 option have comparable environmental impacts, especially with advancements in sustainable material use, both technologies could potentially meet future regulatory requirements and environmental goals. The key would be in demonstrating through lifecycle assessments that both options provide substantial environmental benefits, which would likely involve collaboration across the industry to standardize sustainable practices.

Timo: Thank you for the detailed insights. I look forward to sharing my thesis with you once it's completed.

Participant: You're welcome, Timo. Thank you for involving me in this discussion, and I wish you the best with your thesis.