Report No. **514**

F-gas Use, Scale and Environment (FUSE4i): An Improved Indicative Inventory for Ireland

Authors: Peter Wise, Reena Cole, Narjes Fallah, Mariagrazia Proto and Yvonne Ryan-Fogarty

Lead organisations: University of Limerick

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Rialtas na hÉireann
Government of Ireland

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epa Research

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What did the research aim to address?

The research aimed to address the environmental challenge posed by sulfur hexafluoride (SF_6), a potent greenhouse gas used in various equipment and industries. The knowledge gap focused on understanding SF_6 usage, emissions and alternatives in Ireland. This research is crucial for helping policymakers, environmental agencies and industries mitigate SF_6 emissions, comply with regulations and transition to sustainable practices. The study combined data analysis, stakeholder consultations and innovative modelling to assess SF_6 usage and emissions. It explored alternatives and recommended best practices for SF_6 management, emphasising the need for accurate data collection and reporting.

What did the research find?

The research identified significant SF_6 usage in Ireland, primarily in the power and semiconductor industries. It highlighted the environmental impact of SF_6 emissions and the need for accurate data collection and reporting. A review of information required in environmental impact assessments regarding end-of-life management of SF_6-containing switchgear should be conducted. The findings provide a comprehensive understanding of SF_6 emissions, helping to bridge the knowledge gap and inform strategies for reducing emissions. The research is crucial for helping policymakers, environmental agencies and industries develop effective SF_6 management practices, especially in light of the circular economy aims. The project produced detailed data on SF_6 usage and emissions, along with recommendations for best practices and potential alternatives. This research advances the state of the art by providing a detailed analysis of SF_6 emissions and offering innovative solutions for mitigation. The research assumes accurate self-reporting by industries and may be limited by the availability of comprehensive data from all sectors.

How can the research findings be used?

Implementing the research findings involves enhancing data collection and reporting mechanisms, promoting SF_6 alternatives and increasing stakeholder engagement. Training and certification programmes for SF_6 handling should be expanded. The research supports policy development by providing a detailed understanding of SF_6 emissions and promoting best practices for SF_6 management. It aims to reduce SF_6 emissions, contributing to climate goals. The primary target audience of this research is the EPA's Emissions Statistics Team; however, the Department of Climate, Energy and the Environment and the EPA Office of Environmental Enforcement may also find these insights useful for developing regulations, improving SF_6 management and transitioning to sustainable alternatives. Opportunities include leveraging new EU regulations and enhancing collaboration with industry stakeholders. Future research should address gaps in data from the private sector, explore additional SF_6 alternatives and develop more accurate emission estimation methods.

Project code: 2022-CE-1139

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(2022-CE-1139)

EPA Research Report

Independent scientific research funded by the Environmental Protection Agency

Prepared by

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DISCLAIMER

This report is based on research carried out/data from June 2023 to December 2024. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Sulfur hexafluoride (SF_6) is a synthetic, colourless, odourless, non-flammable and non-toxic greenhouse gas (GHG). It has the highest 100-year global warming potential (GWP) of all GHGs, at 23,500, and one of the longest lifetimes, at 3200 years, and it is therefore more potent than other GHGs, such as carbon dioxide, methane and nitrous oxides.[1] It belongs to a broader group of human-made fluorinated gases (F-gases) that contain at least one fluorine atom. Many F-gases were developed to replace ozone-depleting substances, most commonly hydrofluorocarbons (HFCs), with everyday applications in refrigeration, air conditioning, heat pumps and blowing agents for foams, fire extinguishants, aerosol propellants and solvents. Relative to Ireland, perfluorocarbons (PFCs) and NF_3 are mainly used in semiconductor production. SF_6 is one of the seven GHGs controlled under the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. In line with this, and under its European Green Deal and Circular Economy Action Plan, the EU enacted Regulation (EU) 2024/573, thus amending the F-gas portal quota system, increasing restrictions and the regulation of HFCs, and introducing a target of achieving zero sales of new F-gases and zero F-gas emissions by 2050. The report *Ireland's Final GHG Emissions – 1990–2023*[2] shows an overall decrease in F-gas emissions from 1139 kt CO_2 equivalents (CO_2e) in 2005 to 675 kt CO_2e in 2023, which was 1.2% of the national GHG emissions total. F-gas emissions in 2023 were 6.0% lower than in 2022, following a decrease of 0.5% in the previous year. The decrease can be primarily attributed to a reduction in the use of PFCs and NF_3 in the semiconductor industry. Emissions of F-gases (HFCs, PFCs, SF_6 and NF_3) amounted to 0.68 Mt CO_2e in 2023, compared with 0.04 Mt CO_2e in 1990. The impact of HFC, PFC, SF_6 and NF_3 emissions on inventory uncertainty remains negligible (0.6% contribution) because these gases account for only 1.2% of total GHG emissions in Ireland. However, given that SF_6 has the largest GWP of all F-gases, underestimating emissions of this particular F-gas would have the most significant implications for estimating emissions of F-gases overall.

Only three countries (UK, Switzerland and Australia) use air emissions data analysis to routinely verify inventory emissions data reported as part of the annual UNFCCC submission of emissions data. The rapid expansion of global power demand and faster adoption of renewable technologies, such as wind and solar capacity, over the past decade have given rise to a large bank of SF_6, which currently contributes to the atmospheric burden of SF_6 and will continue to do so throughout the lifetime (30–40 years) of the installed equipment. The observed increase in global installed electrical capacity, in both developed and developing countries, is consistent with the temporal rise in global SF_6 emissions. However, there is no survey, register or publicly available database of the medium-voltage (MV) switchgear and the associated technology used. Bottom-up approaches for measuring emissions have been reported to differ from top-down approaches using Advanced Global Atmospheric Gases Experiment data, among other types of data. Estimating a 2.4% year-on-year increase in the last decade, data from Western Europe show good agreement with UNFCCC reports. In total, 80% of SF_6 produced globally was consumed by switchgear for electrical infrastructure from 1996 to 2003. SF_6 in the electrical power industry is primarily used in high-voltage gas-insulated switchgear (GIS), which consumes $>80\%$ of the SF_6 used, with MV GIS consuming only about 10%. Original equipment manufacturers are actively researching, developing and implementing SF_6-free alternatives. However, with operating lifetimes of 30–40 years, operational and end-of-life emissions need to be balanced with

1 IPCC, 2013. *Climate Change 2013 – The Physical Science Basis*. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

2 EPA, 2025. *Ireland's Final GHG Emissions – 1990–2023*. Environmental Protection Agency, Johnstown Castle, Ireland. Available online: https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/EPA-Final-GHG-Report-Final.pdf (accessed 15 January 2026).

increasing network extensions, primarily renewables and data centres in Ireland.

This project has identified the uses and scale of SF_6 use in Ireland in poorly understood applications identified in the 2023 UNFCCC inventory submission. This included reviewing new data sources for (1) imports of SF_6, (2) particle and electron accelerators (linear particle accelerators, transmission electron microscopes, X-ray equipment) and (3) MV switchgear. The findings should inform Ireland's strategy and policy for achieving zero-emissions targets by 2050 and identify sectors that would benefit from end-of-life management education and training on best practices.

1 Introduction

Sulfur hexafluoride (SF_6) is discussed in Chapter 2, where its properties and relevant information provided in the literature are more fully outlined. Chapter 3 details SF_6 use and the scale of its use through the examination of documented applications and how they relate to the Irish context.

1.1 Project Objectives

The report is structured around the objectives of the FUSE4i – F-gas Use, Scale and Environment – project, during which the research team investigated the uses and scale of use of SF_6 in Ireland in poorly understood applications identified in the 2023 United Nations Framework Convention on Climate Change (UNFCCC) inventory submission. These included new data sources for (1) imports of SF_6, (2) particle and electron accelerators (linear particle accelerators (LINACs), transmission electron microscopes (TEMs), X-ray equipment) and (3) medium-voltage (MV) switchgear. Chapter 4 highlights the environmental concerns of and alternatives to SF_6 use. Chapter 5 summarises the extent of data sources on the current state of SF_6 use that are used to create the national inventory reports (NIRs). It establishes emissions that are known and accounted for and highlights the data gaps that the work presented here aims to address and where future work is required. It extrapolates from international best practice and case studies identified in the literature review. Chapter 6 examines data that are currently available and outlines newly available data that will significantly impact the procedures for inventory compilation. It summarises key data collected as part of the FUSE4i project in three areas: (1) product imports and exports, (2) particle and electron accelerators and (3) privately owned gas-insulated equipment (GIE). Observations and recommendations are outlined in Chapter 7.

2 Contextualising SF_6 Properties and Applications

SF_6 is a synthetic, colourless, odourless, non-toxic and non-flammable gas discovered by French chemists Henri Moissan and Paul Lebeau in 1900. It is about five times denser than air, posing a risk of asphyxiation, and is known for its excellent electrical, thermal and chemical properties, which have enabled significant space and weight savings and improved operational safety in various applications.

2.1 Key Properties and Applications

Dielectric strength: SF_6 has high dielectric strength due to its strong electronegativity, that is, it is capable of absorbing free electrons, making dielectric breakdown possible only at high voltages. It is used in the semiconductor industry for silicon etching.

Thermal conductivity: when pressurised, SF_6 achieves the same dielectric strength as liquid insulators at a lower cost and has 2.5–3 times the breakdown voltage of air or nitrogen. It dissipates heat effectively during arc quenching, resulting in less of a pressure rise than other gases.

Arc quenching self-recovery: SF_6 can self-regenerate after high-voltage (HV) breakdowns, assuming no secondary reactions with other materials.

Toxicity of by-products: the decomposition products of SF_6 can be corrosive and toxic, requiring safety measures. These products hydrolyse in the presence of humidity, forming highly corrosive hydrogen fluoride.

Chemical stability: SF_6 has strong S–F bonds, providing long-lasting chemical stability and excellent infrared absorption, preventing Earth's radiation from escaping. It degrades slowly in the atmosphere, with lifetime estimates ranging from 580 to 3200 years, contributing to radiative forcing for centuries (Ravishankara *et al*., 1993; Christophorou *et al*., 1997; Patra *et al*., 1997; Wang *et al*., 2006; Xu *et al*., 2011; Kovács *et al*., 2017; Ray *et al*., 2017; Solvay, 2018; Simmonds *et al*., 2020; IPCC, 2023; Shi *et al*., 2023).

3 SF_6 Use and Scale of Use: Documented Applications and Relationship to the Irish Context

Globally, about 80% of SF_6 is used as the dielectric gas in the power industry (Palmer, 1996), while the electronics industry and the magnesium industry account for 8% and 4% of total use, respectively. The applications of SF_6 as an adiabatic gas charged in tyres, balls and sports shoes account for about 3% of total use (Simmonds *et al*., 2020). The remaining 5% is used in particle accelerators and in fields such as biotechnology and medical, pharmaceutical and laboratory research (see Table 3.1).

3.1 Gas-insulated Equipment

Use in GIE is the major worldwide application of SF_6, representing about 80% of total SF_6 use (combining utilities and original equipment manufacturers (OEMs)). GIE applications include SF_6 used for arc quenching and insulating properties across all voltage ranges in gas-insulated switchgear (GIS) or substations, gas circuit breakers, ring main units (RMUs), voltage and current transformers, surge arrestors, capacitors and HV cables (Solvay, 2018; US EPA, 2018; Sovacool *et al*., 2021). The two main categories of GIS are described in Table 3.2.

Table 3.1. Global uses of SF_6, as a proportion of total use, across sectoral applications from 1961 to 2003

Use	1961–2003	End 2003	1996–2003
Electric utilities	21%	24%	17%
Electric original equipment manufacturer	60%	54%	63%
Magnesium industry	6%	4%	4%
Electronics industry	4%	13%	8%
SF_6 adiabatic properties	3%	0%	3%
All other uses[a]	6%	5%	5%

[a]Other uses include particle accelerators, optical fibre production, glazing, lighting, biotechnology, medical research, refining, pharmaceutical and laboratory/university research, and sound-proof windows.

Source: Based on data from Smythe (2004).

Both system types have long lifetimes of 30–40 years or longer with life-extension services (Runde and Istad, 2023). In Ireland, there is only one demand-side operator. In comparison, Norway, with a similar population size, has 119 demand-side operators (Rullaud and Gruber, 2020). Annual reports are publicly available and cover a large proportion of the installed GIE owned by the national operator in Ireland. This covers the operator's entire transmission and distribution network, including generation assets to a Tier 3 methodological standard, that is, a standard that includes measurement-based inventories. However, countries with a larger number of participants, like Norway and the USA, face more challenges in encouraging collaboration in the gathering of transmission and distribution data. Consequently, countries like Norway and the USA face more challenges in encouraging collaboration in gathering transmission and distribution data from a larger number of participants (Runde and Istad, 2023). Nevertheless, the collection of the available data in such countries also aims to fulfil the requirements of a Tier 3 methodological standard.

Table 3.2. Main categories of GIS and their descriptions

Main category of GIS	Description
Sealed pressure systems	Hermetically sealed systems. GIE used in MV applications from 1 to 35 kV on the distribution system. Intended to be operated without maintenance for its operating life, with gas handling occurring only at manufacture and decommissioning (US EPA, 2018; Sovacool *et al*., 2021).
Closed pressure systems	Include GIE operating above 35 kV that may require replenishing with SF_6 from an external source to maintain functional pressure (US EPA, 2018).

3.2 The Electronics Industry

The electronics industry encompasses semiconductor processing, microelectromechanical systems, integrated circuits, flat panel display screens and photovoltaic panels, with SF_6 being used as an etchant gas. Plasma chambers selectively remove silicon from wafers, prepare for deposition processes, or clean chamber walls and equipment of silicon deposits. In Ireland, the chip industry began with Analog Devices and Intel, both of which continue to grow and invest. Numerous companies, such as S3, Parthus-Ceva, Cypress, Redmere, Powervation, ChipSensors and FireComms, have since been established. Recent investments have been made by AMD, Infineon and Qualcomm (MIDAS Ireland, 2024). Ireland uses a Tier 2a methodology to estimate emissions from a small number of large semiconductor manufacturers based on gas consumption and emission control technologies. The use of SF_6 in categories such as “thin film transistor”, “flat panel display”, “photovoltaics”, “heat transfer fluid use” and “other electronics industry” was reported as not occurring in Ireland (EPA, 2024). However, additional enterprises, such as those in the Shannon Region (IDA Ireland, 2023), may potentially be involved in manufacturing phosphorescent organic light-emitting diode technology powder materials rather than full organic light-emitting diode displays.

3.3 Magnesium Casting and Aluminium Casting

In the magnesium industry, SF_6 is used as a blanketing gas at various stages, from the production of ingots to processing and recycling. The density of the gas is the main property exploited to displace air and prevent explosive oxidation. In the aluminium industry, SF_6 is used to remove contaminants (Palmer, 1996; Maiss and Brenninkmeijer, 1998; Simmonds *et al*., 2020; Sovacool *et al*., 2021)

Use of SF_6 in Intergovernmental Panel on Climate Change (IPCC) categories 2.C.3 and 2.C.4, covering aluminium and magnesium production, was reported as not occurring in Ireland (EPA, 2024). A company contacted confirmed that it does not undertake die casting in Ireland; instead, it subcontracts all die casting to Europe (Germany) and/or China (Atlas Global, 2014).

3.4 Other Uses

In the main, uses of SF_6 in the biotechnology, medical and pharmaceutical fields are thought to relate to sterilisation and synthesis techniques, for example the reuse of waste SF_6 in medical synthesis applications (Cui *et al*., 2024), whereas uses in laboratory and university research are thought to relate to electron microscopy. Uses in accelerators, microscopes and X-ray equipment are covered later. Little evidence was found for the application of SF_6 in general textile improvement processes using plasma treatment, like in the semiconductor industry in Ireland, or of associated emissions (IPCC, 2006; Solvay, 2018). Table 3.3 details other uses of SF_6 in Ireland found in the literature.

Table 3.3. Additional uses of SF_6, descriptions from the literature and application to the Irish context regarding the SF_6 emissions inventory

Category	Description
Military	SF_6 is used in military applications, particularly in airborne radar systems, e.g. airborne warning and control systems (AWACSs) (2.G.2.a.) (Christophorou *et al*., 1997; IPCC, 2006). A list of aircraft of the Irish Air Corps does not include military reconnaissance planes of the Boeing E-3A type or use of AWACSs principally used by NATO countries (Wikipedia, 2024). Pilatus PC-12 reconnaissance planes are missing the distinctive AWACS radar dome (Flying In Ireland, 2020). Ireland may have military ground-based radar in the future, in addition to the 12 existing civilian radar systems across nine sites (AirNav Ireland, n.d.)
Particle and electron accelerators	SF_6 is used in equipment for university and other research, and industrial and medical particle accelerators (2.G.2.b.) (Smythe, 2004; Solvay, 2018; Lichter *et al*., 2023; Cui *et al*., 2024). This is not covered in Ireland's NIR (EPA, 2024; UNFCCC, 2024) and is covered in more detail in section 6.2.
Filling gas	In double-glazed and sound-proof windows (2.G.2.c.), SF_6 is used as a filling gas to improve energy efficiency and reduce noise by 2–5 dB. Disposal at end of life, on average after 25 years, is currently the main source of emissions following the ceasing of manufacturing in Ireland in 2000. It is thought there are limited options for controlling release at waste-handling facilities (Sovacool *et al*., 2021; EPA, 2024).
Adiabatic properties	In the category "adiabatic properties" (2.G.2.d.), SF_6 is used as a filling gas in sports shoes, balls and tyres. In these applications, the larger molecule has a lower diffusion rate, improving pressure stability and related performance benefits of improved wear, economy, comfort and safety. Adiabatic applications also ceased in Ireland in the 2000s. Each Nike Air shoe contains 2–2.5 g of SF_6, which is expected to be emitted when destroyed at end of life (Sovacool *et al*., 2021; EPA, 2024).
Healthcare applications	SF_6 is reported to be used in medical applications (2.G.2.e.), namely in ophthalmology, as a tamponade for retinal detachment repair. National emissions are roughly estimated using a small sample of gas cylinder consumption rates (EPA, 2024).
Tracer and leak detection	Limited use of SF_6 was reported for the category "gas air tracer in research and leak detectors" (2.G.2.e.), namely for leak detection between 1990 and 2004 from a company that has since ceased trading and for two isolated agricultural tracer experiments in 2009 (EPA, 2024). The leak detection properties of SF_6 have been used for building air exchange measurement systems, district heating piping, vacuum systems and underground tunnels. Atmospheric research and climate science sensors monitor SF_6 levels, and SF_6 has been used to study mass air current, movement, odour and vapour; methane emission metrology experiments (Christophorou, *et al*., 1997; Sovacool *et al*., 2021; EPA, 2024) yielded no further information on this application.
Further uses	• Torpedo propellor quieting, supersonic wind channels (Christophorou, *et al*., 1997). • Optical fibre production, lighting, biotechnology and medical, pharmaceutical and laboratory/university research (Smythe, 2004). • Accelerators Van de Graaf; betatrons and neutron generators; radiation applications in science, medicine, industry, electron microscopes, X-ray equipment production control and non-destructive testing; accelerators for enhancement of polymers and curing (coatings, adhesives and inks on paper, plastic and metal substrates, and composites); multicore wire polymer insulation curing; water and effluent treatment; flue gases purification; sterilisation in healthcare; and decontamination of waste or food (Solvay, 2018). • Biotechnology, medical and pharmaceutical fields, where uses are thought to relate to sterilisation and synthesis techniques, e.g. reuse of waste SF_6 in medical synthesis applications (Cui *et al*., 2024). • Textile, carpet and leather paper with hydrophobicity, stain, dyeing, mechanical and anti-wrinkle improvements (IPCC, 2006).

4 Environmental Considerations

4.1 Manufacturing Locations and Associated Emissions

An assessment of SF_6 supply to the US market alone details the distribution as follows: Russia, 39.5%; China, 21.2%; Germany and South Korea, 25.9%; and Japan, 13.4% (Donnelly and Laverne, 2024). The SF_6 market is growing at a 7.45% compound annual rate, and is expected to increase by US$111.9 million between 2023 and 2028 (Technavio, 2024). Emissions from virgin SF_6, reconditioning and recycling are estimated at <8%, ~0.5% and ~0.05%, respectively (Donnelly and Laverne, 2024). This has led to greater restrictions on virgin SF_6 use and the promotion of reuse processes (Sovacool *et al*., 2021; Cui *et al*., 2024).

4.2 Circularity: SF_6 Reuse and Recovery

The Solvay plant in Bad Wimpfen, Germany, is a key SF_6 producer in Europe, offering virgin SF_6 for HV and MV switchgear and semiconductor manufacturing. Solvay's reuse process integrates used SF_6 into virgin production, meeting the toxicity requirements of International Electrotechnical Commission Standard 60376. Companies like Dilo and BOC provide reconditioning services and reuse programmes. Contaminated SF_6 that cannot be recycled is destroyed at special incineration plants (Dilo, n.d.; BOC Gases, 2005; Solvay, 2013).

4.3 Environmental Impact Assessment

Studies comparing MV air-insulated switchgear and SF_6-insulated switchgear (GIS) highlight the ecological advantages of SF_6 GIS technology, particularly in primary energy use, acidification potential and eutrophication potential, when assessed using life cycle assessment (LCA) techniques. SF_6 technology offers ecological benefits if emissions are kept low and a closed reuse cycle is maintained. However, controlling emissions, especially at end of life, poses challenges, prompting the need for SF_6-free alternatives (Solvay, 2010; Heckmann and Reimann, 2020).

4.4 Life Cycle Emissions

The USA's 2016 Greenhouse Gas Reporting Program estimated SF_6 life cycle emissions as follows: manufacturing, 12%; installation, operation and servicing, 76%; and retiring, disposing and recycling, 12%. Emissions are higher at end of life due to a lack of training and awareness among diverse users (US EPA, 2018).

4.5 Medium-voltage Switchgear User Survey

A survey among European MV switchgear users indicates a preference for environmentally friendly technologies, driven by policies and regulations. However, 57% of respondents are unfamiliar with EU policies on fluorinated gas (F-gas) emissions and are uncertain about viable SF_6-free alternatives. Customers are willing to pay higher prices for switchgear with lower global warming impact or no risk of F-gas leakage (Guetlein and Sebi, 2020).

4.6 SF_6 Destruction

Various abatement technologies are discussed, including incineration, thermal oxidation, catalytic oxidation and non-thermal plasma methods. By-products of SF_6 destruction can be highly reactive, corrosive and toxic (Christophorou *et al*., 1997; Maiss and Brenninkmeijer, 1998; Wang *et al*., 2006; Sovacool *et al*., 2021; Shi *et al*., 2023; Cui *et al*., 2024).

4.7 Alternatives to SF_6

4.7.1 The electronics industry

The electronics industry uses SF_6 as a source of F-radicals for silicon etching. Semiconductor closed plasma etching systems with thermal destruction of SF_6 can reduce residual emissions "to virtually zero" (Maiss and Brenninkmeijer, 1998; de Wild-Scholten *et al*., 2007). On-site F_2 production from hydrogen fluoride was found to be suitable for liquid crystal displays, along with process optimisation, leading to a 40% decrease in emissions despite a 200% increase in production from 2004 to 2010. SiF_4 was found to be suitable for thermal atomic layer etching (Sovacool *et al*., 2021; Cui *et al*., 2024).

4.7.2 Magnesium casting

For magnesium casting, SO_2, HFC-134a, BF_3, HFC-1234ze, $C_4F_9OCH_3$ and $C_6F_{12}O$ have shown promise in replacing SF_6 using technical air or CO_2 as a carrier gas. Substitute gases react and generate a protective surface film similar to SF_6 and result in a reduction in global warming potential (GWP) of at least 98% (Sovacool *et al*., 2021; Cui *et al*., 2024).

4.7.3 Gas-insulated equipment

A 2014 article by the International Council on Large Electric Systems (CIGRE) summarises the history of GIE development and technical brochures that led to the development of International Electrotechnical Commission standards, and it compares alternatives to SF_6 (Glaubitz *et al*., 2014). In 2015, ABB was one of the first companies to offer a whole range of SF_6-free AirPlus ecoGIS switchgear solutions up to 40.5 kV, with a global installed base of 5000 using 3M Novec 5110 fluoroketone $C_5F_{10}O$/air and with similar dielectric insulation benefits and a similar footprint as SF_6 switchgear (3M, 2021; ABB, 2022; Cui *et al*., 2024). 3M has also proposed that Novec 4710 C_3F_7CN could be used as an SF_6 replacement (3M, 2022). Schnieder Electric offers AirSeT MV SF_6-free shunt vacuum interruption and a pure dry "air" (N_2/O_2) solution up to 24 kV (Schneider Electric, 2022).

As of April 2021, the GE Green Gas for Grid (g3) and Hitachi ABB have proposed mixtures of < 10% C_4F_7N, such as 6% C_4F_7N/89% CO_2/5% O_2 for HV GIE. GE's roadmap shows GIS and gas-insulated lines up to 420 kV, and live tank circuit breakers up to 145 kV are already available (GE Grid Solutions, 2023; Cui *et al*., 2024; GE Vernova, 2024).

Health impacts and life cycle assessment for alternatives to SF_6 for gas-insulated equipment

Concerns have been raised about the equipment, given the environmental and human toxicity effects of fluroketone and fluoronitrile (pure and post breakdown). These gases are quicker to break down than SF_6 (as they have a lower GWP and atmospheric lifetime) and do not have the same ability to recombine as SF_6. Limited LCA knowledge was available at the time these concerns were raised (Preve *et al*., 2019). In addition, these gases may become subjects of potential per- and polyfluoroalkyl substance (PFAS) restrictions under the Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) in due course (European Chemicals Agency, 2023). Hitachi and GE produced a detailed C_4–FN handbook in 2023 covering a decade of independent experience, including the technical characteristics of C_4–FN mixtures; health, safety and environmental aspects; and a user guide covering gas handling (Perret *et al*., 2024). Manufacturer and third-party LCAs suggest that using C_4–FN mixtures results in a 59–92% reduction in carbon footprint compared with using SF_6, primarily from the GWP reduction (see Table 4.1).

The toxicity level of arc by-products, from C_4–FN mixtures created by a variety of broad arc condition categories, was used to determine safety measures for various equipment and life cycle stages. By-products from arcing, such as CO and COF_2, increase toxicity. For comparison, used SF_6 is also classified as Category 3. Careful handling of arced SF_6 and C_4–FN mixture gas is required (see Table 4.2).

Table 4.1. Manufacturer and third-party LCA carbon footprint savings for HV GIE

Application	Voltage, kV	C footprint reduction, %	Comment
Dead-tank CB	72.5	59	Saving of 80 t CO_2e
GIS	145	71	Potential reduction of 84% if 100% recycled aluminium is used
GIS	420	78–92	Based on using C_4–FN/O_2/CO_2
Retrofill GIS	420	50	Based on using C_4-FN; reduction would be greater if used earlier in GIS life

CB, circuit breaker; CO_2e, CO_2 equivalents.

Source: Based on data from Perret *et al.* (2024).

Table 4.2. EU classification, labelling and packaging toxicity classification of the arced by-products of C_4–FN mixtures

EU classification, labelling and packaging		Toxicity by broadly applicable arced type	
Category	**Description**	**Arced type**	**Description**
1	Fatal if inhaled	Not applicable	Not applicable
2	Fatal if inhaled	Not applicable	Not applicable
3	Toxic if inhaled	Heavily	Used SF_6, heavily arced C_4–FN mixtures
4	Harmful if inhaled	Normally	C_4–FN mixtures, C_4–FN (technical grade or suitable for reuse)
None	Not categorised	New	New SF_6, non-arced C_4–FN mixtures

Source: Based on data from Perret *et al.* (2024).

The authors of the handbook (Perret *et al*., 2024) stress the importance of the EU's 2023 Green Claims Directive, which requires that accurate LCAs that account for all environmental impacts be conducted; caution against greenwashing; and stress the importance of ensuring that claims are based on equivalent data and standards like the future International Electrotechnical Commission Standard 62271-320 (Perret *et al*., 2024). This echoes similar concerns raised by Schneider Electric (2022). In a 2021 joint statement, 10 transmission and distribution equipment manufacturers (including Eaton, Iljin, Meiden, Mitsubishi, Nuventura, Schneider Electric, Siemens and Toshiba) confirmed that they had already developed or were in the process of developing equipment completely free of F-gases and PFAS gases (Bruyckere, 2022).

5 Potential Modelling Methods Adopted in Other Jurisdictions and Applications

5.1 Early Measurements and Growth Trends

SF_6 was first detected in the 1970s at very low concentrations (< 1 pmol/mol). Reports from the 1990s highlighted a near-linear increase in SF_6 emissions throughout the 1980s, confirming a global rise in the atmospheric burden (Maiss and Brenninkmeijer, 1998). Subsequent reports estimated global growth at 0.29 ± 0.02 pmol/mol/y after 2000 (Rigby *et al.*, 2010), reaching 6.7 pmol/mol by the end of 2008 (Simmonds *et al.*, 2020) and 10 ppt in 2020 (Vojta *et al.*, 2024).

5.2 Recent Trends and Regional Insights

Atmospheric observations and inversion modelling have shown that global SF_6 emission rates rose from 5.9 ± 0.2 Gg/y in 1996 to 7.3 ± 0.6 Gg/y in 2008, continuing to increase by about 24%, to 9.04 ± 0.35 Gg/y, in 2018 (Simmonds *et al.*, 2020). Significant growth in emissions has been noted from non-Annex-I countries (parties to the UNFCCC that are mostly developing countries), particularly those in East Asia, especially China (Simmonds *et al.*, 2020; Vojta *et al.*, 2024). EU countries show a decreasing trend, with emissions dropping from 0.41 Gg in 2005 to 0.25 Gg in 2021, attributed to the implementation of Regulation (EU) 517/2014 (Vojta *et al.*, 2024). In 2018, Western Europe accounted for 3.1% of global emissions (Simmonds *et al.*, 2020), and, in 2021, UK emissions were significantly lower than those of EU countries (Manning *et al.*, 2021). The USA also showed a decreasing trend, while China exhibited an increasing trend (Vojta *et al.*, 2024).

5.3 Top-down Emission Estimates and Methodology

Despite concerns about the underreporting of bottom-up UNFCCC SF_6 emissions, two models covering Western European monitoring sites showed good agreement with UNFCCC inventory reporting. In comparison, China contributed ~ 10 times more emissions than Western Europe, accounting for 36% of global emissions in 2018 (Simmonds *et al.*, 2020; Vojta *et al.*, 2024).

5.4 Implications and Gaps

The findings outlined in sections 5.1–5.3 highlight the importance of independent verification methods for global SF_6 emissions using monitoring networks and top-down estimates. Emissions have risen considerably, especially from rapidly growing economies like China. UNFCCC reports are generally compiled using a bottom-up methodology and traditionally have not incorporated atmospheric data (Maiss and Brenninkmeijer, 1998). The UK, Switzerland and Australia are the only countries that routinely verify their reported inventory emissions as part of their annual UNFCCC reporting (Manning *et al.*, 2021). Performing similar verification in Ireland is plausible, given the well-established monitoring station at Mace Head in County Galway and therefore the availability of national expertise in this respect.

5.5 Fraunhofer Study for Medium-voltage Modelling in the EU

A 2020 study found no public data on installed MV switchgear and technology used in the EU (Heckmann and Reimann, 2020). The authors developed an asset-based model for Germany, France and Spain, then extrapolated for all 28 EU Member States (EU-28), which included the UK at the time of the study, estimating 15 million MV units, with 10 million using SF_6, resulting in a banked volume of 8600 tonnes. The model included public grids, private grids and distributed generation (Heckmann and Reimann, 2020). Three main drivers of SF_6 emissions were identified: network extensions, operational emissions and end-of-life emissions. According to the authors, achieving zero emissions by 2050 could only be achieved through forced replacement with F-gas-free equipment and improved end-of-life management (Heckmann and Reimann, 2020).

6 SF_6 Quantification and Verification

6.1 Existing and Baseline Data

The existing data are publicly available online on the EPA website. Results from the 2024 NIR are summarised below for context and to aid understanding of the scope of the following chapters.

6.1.1 Bottom-up SF_6 emissions report

In 2022, total SF_6 emissions amounted to 16.24 kt CO_2 equivalents (CO_2e), which is 2.3% of all F-gas emissions that year. F-gases themselves account for 1.3% of all reported greenhouse gas (GHG) emissions. SF_6 emissions were split as follows: semiconductor manufacture, 58%; electrical equipment, 24%; and other uses, 18%. The average emissions from 1990 to 2022 for 2.E.1 "semiconductor manufacture", 2.G.1 "electrical equipment" and four subcategories under 2.G.2 "other" were 26.97, >20.37 and >5.99 kt CO_2e, respectively. In 2022, emissions had dropped across all categories to 9.42, >3.91 and >2.92 kt CO_2e, respectively. A generally declining trend began in 1997 due to extensive work undertaken by the semiconductor industry to find alternatives and new processing technologies. The electrical equipment data provider implemented a leak reduction programme from 1997, with improved asset management through developing mobile applications (ESB Networks, 2022).

A Tier 1 method exists for estimating SF_6 volumes used in the following categories:

- **Sound-proof windows** (2.G.2.c): accounting for a lifetime of 25 years was applied; therefore, emissions at disposal are calculated as 100% of the remaining charge after 25 years of leakage at a rate of 1% per annum. The entire quantity of SF_6 remaining inside the window at the end of its life is emitted, because to date no recovery process exists.
- **Sports shoes** (2.G.2): SF_6 use was phased out in 2003/2004, and emissions are not considered to have occurred since 2012 because of the expected lifetime of these products.
- **Retinal repair ophthalmology** (2.G.2.e): emission levels are considered low, with data being extrapolated to cover the entire health system.
- **Air tracers** (2.G.2): this category was a large source of emissions between 1990 and 2004. However, the company in question has ceased trading.

6.1.2 Semiconductor manufacture

Category 2.E.1, "semiconductor manufacture", is the largest contributor to SF_6 emissions in Ireland. The semiconductor industry uses a specific methodology for deriving emissions data equivalent to a Tier 2 method. This is accurate for the estimation of emissions over the reporting period, and the semiconductor industry was excluded from further investigation at this time.

6.1.3 Electrical equipment

Category 2.G.1, "electrical equipment", is the second largest contributor to SF_6 emissions in Ireland. The main data provider is ESB Networks and it covers Ireland's entire transmission and distribution network, including generation. The data collection method employed is a Tier 3 method covering all aspects of the SF_6 life cycle though opening and closing stocks. These data are published by ESB Networks on an annual basis, showing a 45% reduction between 2022 and 2023, from 3.9 to 2.1 kt CO_2e.

ESB Networks set a target of 0.5% SF_6 emissions for 2015, and there was generally a decreasing trend to 0.04% emissions in 2023. A timeline of activities undertaken by ESB Networks and Generation was compiled from annual reports (ESB, 2016, 2018, 2019a,b, 2020a,b, 2022, 2023; ESB Networks 2016, 2017, 2018, 2022, 2023, 2024). For comparison, Regulation (EU) 2024/573 on fluorinated greenhouse gases indicates that OEMs achieve leakage rates of <0.1% (or provide pressure or density monitoring with automated alarms unless equipment contains <6 kg of SF_6) for hermetically sealed equipment. A review of technical specifications from three OEMs offering MV GIE (ABB, Schnieder, Siemens) confirmed compliance with 0.1% leakage rates. Reporting and quantification of SF_6 stocks and emissions does not apply across the fragmented extended MV public and private sectors.

Between 49% and 67% of all ESB Networks sites reported incidents from 2019 to 2022 that were related to SF_6 leaks, handling or storage. This demonstrates the rigour required to drive down emissions. It also highlights the need to establish the extent of emissions from all electrical equipment activities outside the transmission and distribution network. This will be discussed further in section 6.2.6.

6.2 Data Collection and Analysis

Consultation with stakeholders, literature and technical report reviews, and modelling and estimation dimensions were used to establish the knowledge base regarding SF_6 use and stocks in equipment in Ireland. These aspects involved consultation with the project steering committee, universities, the Central Statistics Office (CSO), the Health Service Executive, medical physicists, ESB and other power-supplying entities, F-gas retailers and installers (> 150 emails and > 100 calls (telephone/Microsoft Teams)). Modelling was conducted by amalgamation of OEM data and specific equipment types, IPCC methods and additional data gleaned through the EPA's Licence and Enforcement Access Portal (LEAP).

6.2.1 Import/export data

Harmonized System (HS) codes are six-digit codes from a standardised system developed by the World Customs Organization and used by more than 200 countries worldwide to identify and classify products. In the EU, an additional two digits are applied, extending HS codes and forming Combined Nomenclature (CN) codes. These eight-digit codes are used to track exports out of the EU to non-EU countries and allow for additional customs checks on specific goods, for example those that require permits and certificates. Integrated Tariff of the European Community (TARIC) codes are required when goods enter the EU. These are 10-digit codes and contain detailed information on import duties, taxes and other measures for certain goods. Within the EU, CN codes are used by Intrastat to provide statistics on the movement of goods between EU Member States to the Central Bureau of Statistics. The following CN codes were identified and discussed with the CSO to ascertain the availability of data: **CN 2826 90 00** "Sulfur Hexafluoride (SF_6 gas) purity 99.995% in cylinder (240 cylinders of 50 kg each)" and **CN 2812 90 00** "Halides and Halide Oxides of Nonmetals, Excluding Chlorides and Chloride Oxides". CN 2812 90 00 is expected to cover the majority of general bulk F-gas imports and exports.

The import/export data show a rise in imports from the earliest records in 2000, peaking in 2006 at 604 tonnes, and then dropping by a third to a half in 2007 and 2008, to less than 270 tonnes. From 2009 to 2021, imports were less than 125 tonnes, and in the last few years they have been less than 5 tonnes (see Figure 6.1). Export data show a broadly similar pattern, with a peak in 2006 at 74 tonnes,

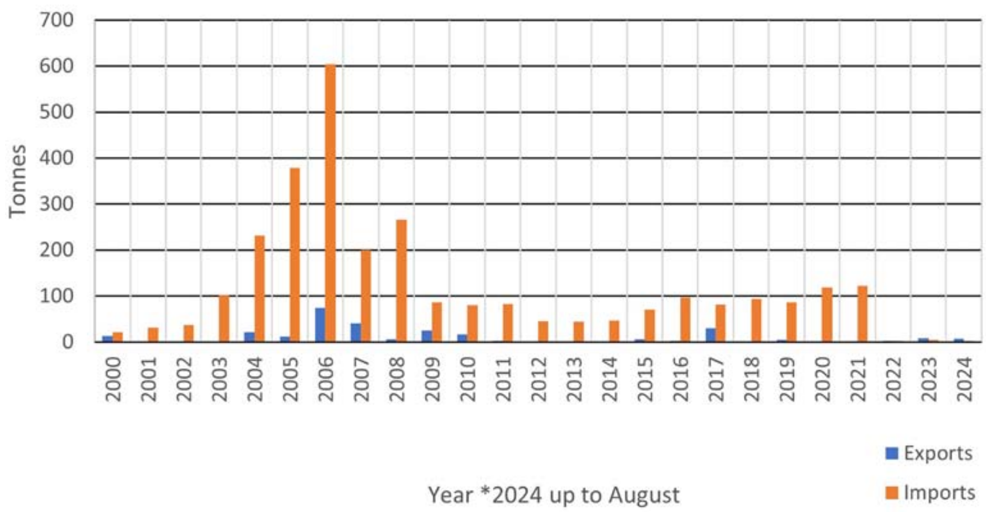

Figure 6.1. CSO import/export data for F-gas CN 2812 90 00, "Halides and Halide Oxides of Nonmetals, Excluding Chlorides and Chloride Oxides".

but at a much reduced volume and with significant fluctuations from year to year, indicating stockpiling or targeted campaigns. More recent years show exports overtaking imports, which may suggest an increase in recycling activity leading up to the introduction of Regulation (EU) 2024/573 on fluorinated greenhouse gases. This latest regulation further restricts the F-gas market quotas introduced in 2014. Our research indicates that other equipment-related HS codes may be useful; these are listed in Table 6.1.

The use of CSO import/export data could complement current F-gas calculation methodologies, which are based on top-down market activity data. Currently, EPA import calculations are based on (1) quantities of industrial gases supplied to chemical suppliers and manufacturers of refrigeration units, and (2) sales data on hydrofluorocarbons (HFCs) and HFC blends. EPA export calculations are based on the market share of refrigeration unit OEM exports. Since October 2024, new CN codes were implemented, adding three 10-digit specific F-gas TARIC codes to the F-gas portal. These codes are 2812 90 00 10 for nitrogen trifluoride (CAS RN 7783-54-2), 2812 90 00 25 for SF_6 entering the EU (CAS RN 2551-62-4) and 2812 90 00 30 for sulfuryl fluoride (CAS RN 2699-79-8). Data started to become available after December 2024 and can be used to aid the creation of reporting methods for SF_6. This will greatly enhance the input–output modelling capacity for all concerned.

6.2.2 Particle and electron accelerators

Particle accelerators were a key focus of the research following recommendations from the UNFCCC in-country review, discussions with sponsors and literature reviews. A particle accelerator increases the velocity and energy of charged particles while containing them in a beam. SF_6 is often used as a dielectric in these HV systems to prevent electrical breakdown. It has a wide range of applications, from applications in kilometre-large colliders in Switzerland to room-size medical and science equipment to even smaller portable systems. The International Atomic Energy Agency's interactive map of accelerators (https://nucleus.iaea.org/sites/accelerators/Pages/default.aspx) indicates that there are currently none of the following in Ireland: (1) accelerator-based neutron sources, (2) boron neutron capture therapy facilities, (3) electrostatic accelerators, (4) synchrotron light sources or (5) X-ray free-electron laser sources.

6.2.3 Transmission electron microscopes

A survey at a university in Ireland identified that SF_6 is used in a specific type of electron microscope, the TEM, which operates at accelerating voltages of 20–300 kV. SF_6 is used for its dielectric properties in these high-tension systems. Web searches identified 10 university microscopy departments in Ireland, with four universities having TEMs that use SF_6. An additional TEM was found at a semiconductor

Table 6.1. Examples of equipment-related HS codes beyond the scope of the current report from which useful CN and TARIC codes may be found

HS code heading	Description
8418	Refrigerators, freezers and other refrigerating or freezing equipment, electric or other; heat pumps other than air-conditioning machines of heading 8415
8414	Air or vacuum pumps, air or other gas compressors and fans; ventilating or recycling hoods incorporating a fan, whether or not fitted with filters; gas-tight biological safety cabinets, whether or not fitted with filters
8415	Air-conditioning machines, comprising a motor-driven fan and elements for changing the temperature and humidity, including those machines in which the humidity cannot be separately regulated
8535	Electrical apparatus for switching or protecting electrical circuits, or for making connections to or in electrical circuits (e.g. switches, fuses, lightning arresters, voltage limiters, surge suppressors, plugs and other connectors, junction boxes) for a voltage exceeding 1000 V
8543	Electrical machines and apparatus, having individual functions, not specified or included elsewhere in this chapter
	Specifically 1000 00: Electrical machines and apparatus, having individual functions, not specified or included elsewhere in this chapter – particle accelerators
9022	Apparatus based on the use of X-rays or of alpha, beta, gamma or other ionising radiation, whether or not for medical, surgical, dental or veterinary uses, including radiography or radiotherapy apparatus, X-ray tubes and other X-ray generators, high tension generators, control panels and desks, screens, examination or treatment tables, chairs and the like

manufacturer, totalling nine TEMs containing SF_6 from three different OEMs. Two OEMs had models that did not use SF_6.

The total SF_6 in these microscopes was calculated to be approximately 68.8 kg, with an additional 103 kg stored in new and reclaimed gas cylinders for service and maintenance, equating to 4047 t CO_2e of stored gas. Leakage rates were not formally recorded, but one estimate was 0.2 kg from a 2.33 kg charge over 13 years, or 0.007 kg/kg charge/y, about half the IPCC guideline of 0.013 kg/kg charge/y. Emissions from the microscopes were calculated using three approaches: (1) 0.007 kg/kg charge/y, (2) Tier 1 (< 0.3 MV 115 kg charge and 0.013 kg/kg charge factor) and (3) Tier 2 (calculated charge and 0.013 kg/kg charge factor). These approaches resulted in emission estimates of 10.7, 316.2 and 21.0 t CO_2e, respectively, representing 0.07%, 1.95% and 0.13% of total 2022 SF_6 emissions, respectively.

Most TEMs have pressure measurement devices to detect leaks and prevent arcing damage, with some facilities having additional SF_6 alarm gas monitoring systems. Several universities had machines at or beyond end of life, posing challenges for SF_6 recovery and disposal. Awareness of SF_6 as a potent GHG was evident among users/operators, but knowledge of the specifics of regulations and legislative requirements was sometimes lacking. Manufacturers generally understood legislative requirements, with some performing service work for users, while others worked with third-party SF_6-certified companies.

6.2.4 Medical linear particle accelerators

LINACs use SF_6 because of its dielectric properties to prevent wave arcing in the radio frequency waveguide (Lichter *et al*., 2023). They have high accelerating voltages (6–25 MV) and are not yet included in the NIR. The radio frequency power is fed into the accelerating waveguide via an SF_6-filled rectangular waveguide (IPCC, 2006). Several approaches were used to quantify the number of medical LINACs in Ireland. Initial web searches and information from the National Cancer Registry Ireland estimated that there were 38 machines in 2024. A manufacturer confirmed that there were 39 LINACs in Ireland, similar to the International Atomic Energy Agency's Directory of Radiotherapy Centres list of 42 MV therapy machines in 2017.

Manufacturers provided SF_6 amounts per make of LINAC, totalling 15.5 kg of SF_6 or 364 t CO_2e. An average leak rate of 0.1825 kg/y was found (Lichter *et al*., 2023). Emissions were calculated using three approaches to give the following estimates: (1) 167.26 t CO_2e, (2) 916.5 t CO_2e and (3) 728.5 t CO_2e. These estimates represent 1%, 5.6% and 4.5% of 2022 SF_6 emissions, respectively.

Manufacturers are working to reduce or replace SF_6, with the aim of having SF_6-free machines by 2030. Pressure devices prevent operation during pressure loss. Some designs have built-in reclaim and top-up systems. Discussions with a radiologist indicated no SF_6 use in magnetic resonance imaging equipment, medical X-ray equipment, computed tomography scanners or ultrasound equipment in Ireland.

Medical LINACs have an estimated operating life of 15–20 years. The Directory of Radiotherapy Centres website indicates that almost half of the installed base is at the end of its life. One OEM has specific SF_6 handling and recovery procedures, engaging certified contractors for end-of-life management. The other OEM defers waste gas management to the treatment centre, which typically engages certified contractors.

6.2.5 X-ray equipment

X-ray generators are used in the medical, industrial, research and security sectors, with uses ranging from simple film-based imaging to advanced digital nano-scale 3D computed tomography. SF_6 applications were narrowed down to specific groups with guidance from medical physicists and leading manufacturers. Large cabinet-based systems use oil-based insulation, while most SF_6 applications are in portable industrial non-destructive testing X-ray equipment, reducing regulatory and administrative burdens. SF_6's excellent dielectric properties prevent arcing in HV systems. Portable equipment, weighing around 35 kg with SF_6 insulation, is small and lightweight, enabling easy handling in cramped spaces. Substituting oil would increase weight and size, making the equipment harder to manoeuvre. Mobile units can operate for up to 30 years without SF_6 loss, with pressure monitored by software to prevent damage. OEMs provide well-defined service networks, discouraging self-repairs. Many X-ray practices in Ireland require registration or licensing, and the EPA most likely has records of all portable X-ray devices for industrial radiography, useful for estimating the scale of SF_6 use (EPA, 2025).

6.2.6 Privately owned gas-insulated equipment

Top-down air emissions modelling suggests bottom-up NIR reporting methods fell short by 27.5–55.5% in 2018 (2.5–5 Gg/y of 9.04 Gg/y). Annual average sales indicate that SF_6 is primarily used in electrical equipment (80%), with smaller percentages being used in magnesium production (4%), electronics (8%), adiabatic applications (3%) and other uses (5%) (Simmonds *et al*., 2020).

MV GIE at 24 kV or less is hermetically sealed, with welded cabinets and crimped, welded filling pipes. These units have operational lifetimes of over 30 years, such as the first installed wind farm, Oweninny (Bellacorick), which was installed in 1992 (ESB, 2024). SF_6 release is most likely due to mechanical failure during end-of-life handling. Specialist training and equipment exist for gas-tight drilling and SF_6 removal at end of life. Most infrastructure substations are 24 kV–230 VAC RMUs, with 0.3–2.5 kg of SF_6 being in hermetically sealed units with low leak rates. Preventative maintenance to replace gaskets and prevent leaks is required every 4–6 years for equipment above 24 kV, with the use of larger gas amounts meaning more opportunities for leaks (see Table 6.2).

In 2023, 33.7% of Ireland's energy generation came from wind (SEAI, 2024), making wind the largest renewable sector in Ireland (ESB Networks, 2024). By October 2024, there were 272 wind farms with 1367 wind turbines. Approximations of GIE per wind farm included one RMU per wind turbine generator, stepping up voltage from 230 V–6.6 kV to 10–24 kV, and the number of additional GIS units for farms with more than five turbines was estimated as follows:

- 38 GIS units for 10 kV or 20 kV network connections;
- 127 GIS units for 38 kV network connections.

Farms with 110 kV network connections were excluded to avoid double counting.

Emission rates for wind farm MV equipment were low, with failures more likely in thermal plants. A university survey found no leaks in 25 years of MV infrastructure. A Solvay-led consortium reported that MV GIS use contributed less than 0.005% to the greenhouse effect in Germany (Solvay, 2018). IPCC 2006 guidelines suggest default emission factors of 0.2–2.6% for HV closed pressure systems as follows (IPCC, 2006):

- Tier 1 MV sealed pressure default emission factor, 0.002; lifetime, > 35 years; fraction of charge remaining at retirement, 0.93;
- Tier 1 HV closed pressure default emission factor, 0.026; lifetime, > 35 years; fraction of charge remaining at retirement, 0.95.

In Ireland, from 151 wind turbines installed since 2007, only one emission event occurred due to a rare mechanical failure, losing 1.25 kg of gas equating to 0.039% kg/kg charge/y. Vattenfall data indicate that Europe's 100,000 wind turbines, with ~3 kg SF_6 each, had emissions of 900 kg over 6 years (0.05% kg/kg charge/y) (Tang, 2019). Using the IPCC 2006 Tier 1 methodology (IPCC, 2006); see Figure 6.2 and Table 6.3), potential SF_6 emissions from Ireland's wind energy sector were estimated at 16–30 t CO_2e from banks of 42–62 kt CO_2e, representing 0.1–0.19% of 2022 SF_6 emissions.

Table 6.2. Typical SF_6 ranges for wind farm equipment

Equipment type	Operating voltage, kV	SF_6 range, kg	Type	Maximum permitted emissions, % (UK Emissions Trading Scheme/EU regulations)
Typical wind turbine generator RMU	0.230–6.6	0.3–2	Hermetically sealed	< 0.1
Typical farm RMU	24	0.3–2.5	Hermetically sealed	< 0.1
Typical farm GIS	38–110	5–9	Closed pressure sealed	< 0.5
Wind farm GIS	10 or 20	0.285–3.24	Hermetically sealed	< 0.1
Wind farm GIS	38	2.5–4	Closed pressure	< 0.5
Wind farm GIS	110	5–11	Closed pressure	< 0.5

Source: Data provided courtesy of ESB Networks.

EQUATION 8.1
DEFAULT EMISSION FACTOR METHOD
Total Emissions = Manufacturing Emissions + Equipment Installation Emissions + Equipment Use Emissions + Equipment Disposal Emissions

Figure 6.2. Equation 8.1, for calculating Tier 1 emissions from electrical equipment, from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 3 – Industrial Processes and Product Use*. Source: IPCC (2006).

Table 6.3. Assumptions used for calculating Tier 1 emissions

Assumptions	Tier 1 Equation 8.1 definitions[a]
No manufacturing found in Ireland. Zero.	Manufacturing emissions = manufacturing emission factor × total SF_6 consumption by equipment manufacturers
MV is sealed during manufacture. Zero.	Equipment installation emissions = installation emission factor × total nameplate capacity of new equipment filled on-site (not at the factory)
0.2% IPCC 2006 default emission value (IPCC, 2006). Only emissions considered in Tier 1 methods reported here.	Equipment use emissions = use emission factor × total nameplate capacity of installed equipment The “use emission factor” includes emissions due to leakage, servicing and maintenance as well as due to failures
Earliest wind farm (Oweninny, Bellacorick; 1992) still operational: < 35 years; 40–50 years (Runde and Istad, 2023); 60 years (Heckmann and Reimann, 2020). Limited data. Assume limited retirements.	Equipment disposal emissions = total nameplate capacity of retiring equipment × fraction of SF_6 remaining at retirement

[a]Definitions from Equation 8.1 in Volume 3 of the IPPC’s 2006 guidelines on national GHG inventories (IPCC, 2006).

The Fraunhofer Institute report on EU-28 MV modelling (Heckmann and Reimann, 2020) was used to estimate the potential scale of MV GIS infrastructure in Ireland. As of 2022, the EU-28 had 15 million MV switchgear units, of which 10 million MV units were estimated to have SF_6 GIS. EU-28 electricity generation amounted to 2701 TWh and in Ireland it amounted to 33 TWh (Eurostat, 2024). Scaling EU-28 MV units by electricity generation estimates that there were 122,000 MV units in Ireland in 2022. In comparison, ESB Networks reported that there were 24,000 MV GIS units in its network (ESB Networks, 2024). This suggests the private sector could hold five times the amount of MV equipment that ESB Networks holds.

6.2.7 Approaches used to ascertain SF_6 emissions from the private sector

It is important to ascertain SF_6 emissions from facilities in the private sector that do not report emissions to the EPA and are not licensed under the Industrial Emissions Directive. Several approaches were undertaken to find a way to access data in the private sector, including a university and hospital survey; following the data requirements and owners using the regulations and legislation; discussion with the ESB Group; and modelling using information from existing databases and sources.

Existing data available to the EPA

The Pollutant Release and Transfer Register database had records of SF_6 releases for two licensed sites. One is a semiconductor manufacturer, which is one of two relatively large semiconductor manufacturers based in Ireland. The other is an energy generation site. Both have longstanding relationships with the EPA and have provided annual disclosures for many years. Reviews of the Environmental Data Exchange Network portal submissions from energy licence holders identified five non-ESB-licensed sites that filed details of F-gas incidents – only 1 of the 12 incidents was SF_6 related. The other 11 incidents relate to losses of refrigerant from heating, ventilation and air-conditioning (HVAC) units. It is not clear if these *ad hoc* emissions were included in NIRs. Two of the non-ESB sites, Amazon and Runways, might be reclassified as data centres.

ESB reports also include perfluorocarbon (PFC) gas emissions from fluid-filled cables from 2017 (ESB Networks, 2017) (Figure 6.3). These data do not appear to be included in NIRs. Category 2.E.1 includes PFC emissions from only the semiconductor industry.

Other available data sources

F-gas tracking software is also available. ESB has been using a mobile application-based tool to achieve world-class Tier 3 emissions tracking since 2021 (ESB Networks, 2022). The use of this software solution could be promoted to all certified F-gas-handling companies that service SF_6 equipment, and then these companies, working with software providers, could provide anonymised data to the EPA in annual reports. The EPA already holds the list of the approved certified contracting companies providing these services. SF_6 training is not currently available in Ireland.

F-gas training and certification. The EPA website suggests that FGR Limited provides training for all F-gases. However, discussions with certified SF_6 companies identified that this was not the case. Quality and Qualifications Ireland (QQI) has approved Limerick and Clare Education and Training Board (LCETB), City of Dublin Education and Training Board (CDETB) and ECAC (a refrigeration, HVAC, heat pump and F-gas training and consultancy firm) courses focused on HVAC and fire protection (see Table 6.4 for details of training courses).

QQI-approved courses in Ireland do not cover SF_6. Personnel needing SF_6-specific certification must obtain training abroad, such as from Dilo in Germany and EA Technologies in the UK, in accordance with EU regulations and accredited by an EU body. These certificates must be granted by the EPA and provided to the European Commission in line with Ireland's European Union (Fluorinated Greenhouse Gases) Regulations 2022 (S.I. No. 404/2022). Only certified individuals can install, service, maintain, repair or decommission SF_6-containing GIE, including for gas recovery and limited leak checking.

Since 31 March 2025, any entity placing >4.25 kg of SF_6 in products or equipment has had to report this to the European Commission (Regulation (EU) 2024/573). Given that individual items of MV GIE can contain 0.2–11 kg of SF_6, most manufacturers need to provide data. Collecting data from the fragmented private sector, following ESB's Tier 3 model, presents opportunities. Certified persons recorded by the certification body could unlock access to private sector data, promoting best practices across all sectors.

Ireland's leading SF_6 contractor has records for private sector operators across multiple industries, but these remain siloed. OEMs know what is installed but are not necessarily responsible for ongoing service and maintenance. Their personnel would fall under the certified persons' requirements. Additionally, decommissioning bonds required by local government planning authorities are around €50,000 for a €50 million wind farm development, primarily for visual remediation. Environmentally sensitive remediation could cost around €3 million.

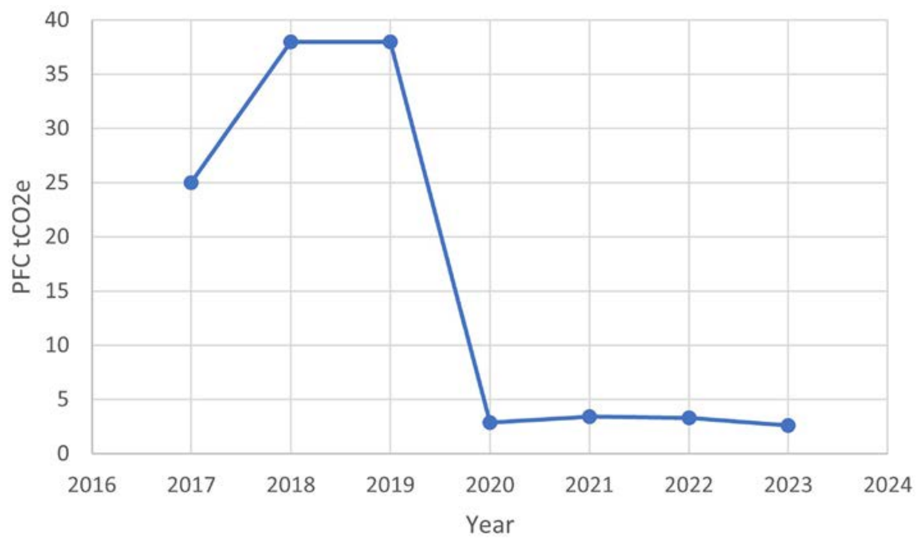

Figure 6.3. PFC gas emissions from ESB Networks reports.

Table 6.4. QQI-approved courses available in Ireland

Course	Level	Category	Organisation/link	Link/course validated until
Mobile HVAC	5	Not applicable	CDETB[a] LCTEB[b]	1 December 2026
Stationary refrigeration Air conditioning Heat pumps Refrigeration on trucks and trailers	5	2	LCETB[c] ECAC[d]	31 December 2026
Stationary refrigeration Air conditioning Heat pumps Refrigeration on trucks and trailers	5	1	LCETB[e] ECAC[f]	31 December 2027

[a]https://irq.ie/courses/level-5-specific-purpose-certificate-in-handling-f-gas-in-mobile-airconditioning-systems?id=81e827ef-59a0-45bb-aac7-c3fcfadcd152&ref=%257B%257D (accessed 19 January 2026).

[b]https://irq.ie/courses/level-5-specific-purpose-certificate-in-handling-f-gas-in-mobile-airconditioning-systems?id=aedbe663-04ee-46f2-9c03-79041a4903b6&ref=%257B%257D (accessed 19 January 2026).

[c]https://irq.ie/courses/level-5-specific-purpose-certificate-in-fgas-handling-rachptt-systems-category-2?id=e2ed4048-42be-4e1a-b464-1d6cfd5443c7&ref=%257B%257D (accessed 19 January 2026).

[d]https://irq.ie/courses/level-5-specific-purpose-certificate-in-fgas-handling-rachptt-systems-category-2?id=a3f57fc4-2dfc-4279-ab2c-878319000310&ref=%257B%257D (accessed 19 January 2026).

[e]https://irq.ie/courses/level-5-specific-purpose-certificate-in-fgas-handling-rachptt-systems-category-1?id=92f7bc3c-e006-4700-87ca-1de6e7254970&ref=%257B%257D (accessed 19 January 2026).

[f]https://irq.ie/courses/level-5-specific-purpose-certificate-in-fgas-handling-rachptt-systems-category-1?id=b51e2c6e-6cfa-4e18-962c-ff00ab6d9060&ref=%257B%257D (accessed 19 January 2026).

Trade bodies and associations

After contacting several trade associations, none was found to have knowledge of SF_6 in the private sector. Data from the annual EPA NIR are reused by Wind Energy Ireland and the Electricity Association of Ireland to support policy, without considering fugitive SF_6 emissions from private sector operators. The Energy Networks Association collaborates with transmission and distribution operators in the UK and Ireland to reduce emissions (Energy Networks Association, 2017), with ESB working to a Tier 3 methodology. ESB's efforts have significantly contributed to reductions recorded in Ireland's inventory reporting, with an average of 59.7% of their environmental incidents being related to SF_6 over the last 5 years.

The standard has been set for operators in the private sector to provide access to their data. Whether they are licensed or not, or believe that there are legal exclusions, SF_6 will become an increasingly restricted commodity. Further restrictions on virgin gas, reducing quotas to zero on the market by 2050, and the decades-long life of the equipment will all play into this scenario. Sharing data and adopting best practices for reducing SF_6 emissions, including modern SF_6-reduced or SF_6-free equipment, is in the private sector's best interest. CIGRE and OEMs have funded technical work on SF_6 technology improvements. EirGrid and ESB might set standards for HV and MV equipment installations in the private sector. Ultimately, operators are responsible for adhering to national and EU regulations.

7 Recommendations

Several issues were identified by the research team as being of interest in the wider context of enhancing reporting mechanisms that do not necessarily contribute to refining the SF_6 inventory directly. Rather, these are areas where cross-collaboration is required between various EPA units and governmental bodies to accelerate decarbonisation, enhance planning and facilitate the circular economy.

7.1 Planning Future Infrastructure: SF_6 and F-gas Considerations

7.1.1 Wind energy environmental impact assessments

While researching GIS and associated SF_6 emissions, the research team examined environmental impact assessment (EIA) reports (EIARs) pertaining to wind energy installations and associated substation constructions. The EIA Portal is maintained by the Department of Housing, Local Government and Heritage and displays applications for development consent accompanied by an EIAR submitted since 16 May 2017, which is the date on which Directive 2014/52/EU, on the assessment of the effects of certain public and private projects on the environment, became applicable. Installations for harnessing wind power for energy production (wind farms) are listed in Annex 2 to Directive 2014/52/EU, and can be subject to EIAR requirements after screening. The *Draft Revised Wind Energy Development Guidelines* (Government of Ireland, 2019) outline that the "EIAR submitted with the planning application addresses the cumulative impacts of the whole project" and that "technologies and substances used" are part of this. Wind energy developers construct the turbines, ancillary works and substations, and at the end of construction the ownership of the site's substation is transferred to EirGrid. This explains why the majority of EIARs examined make no reference to SF_6 in switchgear or lifetime management implications such as commissioning, preventative maintenance, catastrophic failure or end-of-life management. In one case, we found a query from members of the public regarding SF_6, and the response given by the developer was that "SF_6 will not be required for the underground cable and very small amount is required for arc suspension within the circuit breakers at the substations – will not give rise to risk of major accident". While EIARs for Annex 1 activities are directly related to Industrial Emissions Directive licence applications, the EPA may need to reexamine the end-of-life and decommissioning activities associated with Annex 2 activities.

7.1.2 Medium combustion plant regulation requirements

Medium combustion plant regulation requirements, brought about by Directive (EU) 2015/2193, represent a major challenge in raising regulatory awareness, particularly among private organisations. Representatives at the EPA Clean Air Event 2024 suggested that local authorities' planning review processes could provide a good opportunity to communicate regulations with applicants and ensure compliance. An addendum of information required with respect to F-gas use and an inventory of equipment containing F-gases/GHGs could also be sought alongside planning applications.

7.2 SF_6 and Implications for the Circular Economy

Currently, Lists of Waste codes from the European Waste Catalogue are ineffective in tracking SF_6 material flows. However, integrating them into the LCA of F-gas flows for reuse, recovery, recycling and destruction presents a significant opportunity. Collaboration with the National Waste Collection Permit Office is advised.

Many chemical suppliers are adopting "chemical leasing" as part of their circular economy strategies. In this model, the manufacturer or an agent retains ownership of chemicals, extending the use of long-lasting, stable chemicals like SF_6. This approach ensures management over the complete life cycle.

Manufacturers have advanced the development of detailed guidance on SF_6 recovery and reuse. Policymakers and associated agencies should prepare for this shift in market dynamics.

7.3 Observations and Future Research Implications

While SF_6 is the primary focus of this research, other concerns were noted:

- While Ireland's SF_6 emissions are relatively low, many emissions are generated at the point of manufacture and loading of SF_6-containing equipment. The EU should press for international action on SF_6 and a global acceleration of efforts to eliminate its use. While not an ozone-depleting substance, actions and prioritisations afforded to HFCs under the Montreal Protocol should be considered for SF_6.
- R-134A refills are easily available to the public, bypassing certified personnel regulations (Halfords, 2025). A scoping review is needed to address this issue.
- SF_6 in waste electrical and electronic equipment poses a release risk if not controlled at waste sites. For example, one YouTube video shows a member of the public releasing SF_6 from a recovered portable X-ray voltage generator (high1voltage1rules, 2017).
- Public concern about F-gases is likely to focus on R-1234ez, used in battery cooling. As Ireland electrifies, battery storage demand will rise for electric vehicles, solar farms and data centres. However, R-1234ez has a GWP of less than 1.
- SF_6 in physics demonstrations: The use of SF_6 in physics demonstrations indicates a lack of public awareness of the environmental implications of using this F-gas (Da Vinci Kids, 2019).
- The EPA Radiation Protection Team holds valuable information on particle and electron accelerators, including LINACs and portable X-ray equipment, which could be useful for future inventories and end-of-life risk assessments.
- CSO data track general F-gas movements, including in the EU, such as in Germany, and in the UK. The application of an administrative tax on F-gases as a way of tracking imports and end use merits further investigation.
- Inverse emissions modelling using the methods and expertise in air monitoring of Mace Head Station in County Galway could validate bottom-up inventory calculations if more local SF_6-monitoring data could be compiled.
- Representative bodies such as Wind Energy Ireland could validate SF_6 emissions methodologies for wind farms and champion end-of-life management. Irish Solar Energy could perform a similar role for other renewable energy sectors.

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Abbreviations

CDETB	City of Dublin Education and Training Board
CIGRE	International Council on Large Electric Systems
CN	Combined Nomenclature
CO_2e	Carbon dioxide equivalents
CSO	Central Statistics Office
EIA	Environmental impact assessment
EIAR	Environmental impact assessment report
F-gas	Fluorinated gas
GHG	Greenhouse gas
GIE	Gas-insulated equipment
GIS	Gas-insulated switchgear
GWP	Global warming potential
HFC	Hydrofluorocarbon
HS	Harmonized System
HV	High-voltage
HVAC	Heating, ventilation and air conditioning
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCETB	Limerick and Clare Education and Training Board
LINAC	Linear particle accelerator
MV	Medium-voltage
NIR	National inventory report
OEM	Original equipment manufacturer
PFAS	Per- and polyfluoroalkyl substances
PFC	Perfluorocarbon
QQI	Quality and Qualifications Ireland
RMU	Ring main unit
TARIC	Integrated Tariff of the European Community
TEM	Transmission electron microscope
UNFCCC	United Nations Framework Convention on Climate Change

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáilaguscóraischomhlíontacomhshaoiléifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

> Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
> Sceitheadh fuíolluisce uirbigh;
> Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
> Foinsí radaíochta ianúcháin;
> Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

> Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
> Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
> Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
> Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
> Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
> Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
> An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

> Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
> Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
> An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
> Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

> Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
> Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

> Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
> Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
> Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

> Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
> Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
> Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
> Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
> Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

> Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
> Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

> Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
> Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
> Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
> Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

> Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
> An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
> Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
> Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

> Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Táan GCCá bainistiúagBordlánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.