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assessing the availability of alternatives to fluorinated greenhouse gases in switchgear and related equipment, including medium-voltage secondary switchgear

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1. Introduction

Regulation (EU) No 517/2014[1] on fluorinated greenhouse gases (hereinafter the Regulation) requires, in Article 21(4), the Commission to assess whether cost-effective, technically feasible, energy efficient and reliable alternatives exist, which make the replacement of fluorinated greenhouse gases (F-gases) possible in new medium voltage secondary switchgear.

This report responds to this requirement under the Regulation. In addition it also focuses on new medium voltage primary switchgear and switchgear with higher voltages as well as generator circuit breakers and other equipment related to switchgear. The report does not consider retrofitting existing switchgear.

The F-gas targeted in this report is sulphur hexafluoride (SF_6), which has been used in switchgear for decades as insulation material and current breaking medium. With a global warming potential (GWP) of 22 800[2] SF_6 is the most powerful greenhouse gas known.

The report is based on technical work undertaken for the Commission, including extensive consultations with stakeholders as well as deliberations within the Consultation Forum[3] established pursuant to Article 23 of the Regulation. In particular, it should be noted that information about costs and market developments are based on information provided by manufacturers.

2. Current status of alternatives to SF_6 in different types of equipment

2.1. Different types of switchgear equipment

Switchgear are a combination of switches, fuses or circuit breakers that control, protect and insolate various types of electrical equipment e.g. by avoiding current overload that would destroy the equipment. Many different types of switchgear exist. In this report different types are distinguished based on:

- voltage level;
- electricity network level;
- insulation medium; and,
- switching device mechanism.

The voltage levels: low, medium, high and extra high voltage

For voltage levels, the report follows the convention of the International Electrotechnical Commission standards (IEC, 2003) and distinguishes between the following voltage levels:

1 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2014.150.01.0195.01.ENG

2 GWP values are taken from Annex I and II of the Regulation.

3 Meetings of the F-gas Consultation Forum established in accordance with Article 23 of the F-gas Regulation: https://ec.europa.eu/clima/events/articles/0106_en. The link includes a briefing paper that provides further references of sources used to establish the current findings.

Low voltage (LV)	< 1kV
Medium voltage (MV)	1 kV – 52 kV
High voltage (HV)	> 52 kV and < 150 kV
Extra high voltage (EHV)	> 150 kV

The network levels: transmission and primary and secondary distribution

Equipment is also classified by the type of electricity grid where it is used, i.e. either in electricity transmission lines or distribution lines.

Transmission refers to the transportation of large amounts of electrical power over long distances from power plants to sub-stations, while distribution is the delivery of electrical power from sub-stations to the consumer. The distribution level is also divided into primary and secondary distribution.

In primary distribution switchgear are at the interface with the transmission network. In general, these interfaces are indoors in dedicated substations, where environmental parameters like temperature and exposure to weather conditions like rain or snow are controlled.

In secondary distribution switchgear are at the interface with lower voltages and the final customers. These medium/low voltage distribution transformers are located in cabinets near users' premises. The dominant type of switchgear in public networks are ring main units (RMU), which are modular, compact, sealed assemblies of the switching devices needed. Compared to primary distribution, various additional constraints apply: installation space is usually very limited, environmental parameters like temperature or humidity are often not controlled and the equipment may be installed in public areas.

There is a correlation between the network level and relevant voltage levels. Transmission of electricity to substations (usually over long distances) requires higher voltage than distribution of electricity from the substation to the consumer. In Europe, low and medium voltages are mostly used for distribution, while extra high voltage is generally used for transmission. High voltage networks may be used for both transmission and distribution, depending on the country.

Voltage level	**Distribution level**
Low voltage (LV)	Secondary distribution
Medium voltage (MV)	Secondary distribution Primary distribution
High voltage (HV)	Primary distribution Transmission
Extra high voltage (EHV)	Transmission

The insulation medium: air, gas, solid or liquid

The medium that provides insulation in a switchgear can be either air, gas, solid or liquid material.

Gas Insulated Switchgear (GIS) typically use SF_6. Alternatively, SF_6-free GIS employ gas being mixtures of natural gases such as technical air (nitrogen and oxygen) or CO_2. In order to increase the insulation strength, sometimes small quantities of synthetic, fluorinated substances (mostly fluoronitriles and fluoroketones) are added to the gas. These blends have a much lower climate impact than SF_6.[4]

Air-insulated switchgear (AIS) use ambient air as the insulation medium. With air the physical dimension of the switchgear tends to be relatively large and the potential exposure of electrical parts to environmental factors such as humidity, dust etc. may be more problematic. Thus such equipment is mainly used in primary distribution settings, where environmental factors can be more easily controlled and space constraints are less severe compared to secondary distribution settings.

Solid (SIS) and Liquid (LIS) solutions for secondary distribution have been commercially available for years. However, the market share in Europe is still in a lower single digit percentage, partly due to the slightly higher investment costs compared to SF_6 products. However, in some Member States the market share in local regions is relatively high thanks to cooperation with the final users that adopted this technology. State of the art SIS designs combine solid insulation with air at ambient pressure in a hermetically sealed tank and, hence, can also be seen as a type of GIS. In contrast to AIS, environmental factors like dust, dirt, salt, humidity do not affect the performance of the equipment.

The switching medium: vacuum or SF_6

Switching devices protect equipment from damage by interrupting the electrical current flow after a fault is detected. Two main devices exist: circuit breakers and load break switches-fuse combinations.

Circuit breakers operate by the opening of their contacts to interrupt the circuit once a fault is detected; the generated arc is quenched in the used medium. For circuit breakers, the creation of a vacuum is the dominant solution.

In a load break switch-fuse combination, the load break switch disconnects the circuit, while the fuse provides protection against short-circuit and electric arcs. Load break switches mostly use SF_6.

[4] Fluoroketones are considered to have a GWP below 1 and fluoronitriles are considered to have a GWP of 2 100 CO_2 equivalent. The chosen composition of the blends depends on the system where they are used. By way of example in cases where the blend with fluoronitrile consists of 96% or 80% CO_2 and 4% or 20% fluoronitriles the GWP of the blends are 180 or 500 CO_2 equivalent, respectively. This means that compared to SF_6 the climate impact of these blends correspond to 1- 2% of the GWP of SF_6.

2.2. Alternatives to SF_6 in medium voltage switchgear

The feasibility of using SF_6-free solutions for insulation and for breaking depends in particular on the voltage level and the network level.

2.2.1 Medium voltage switchgear in primary distribution

For medium voltage switchgear in primary distribution SF_6-free alternatives are already a reality. As regards the insulation, AIS have a significant market share (40% to 80%, depending on the manufacturer) in applications where space and environmental factors are not an issue, i.e. in rooms with controlled climate offering sufficient space. SF_6-free GIS alternatives also exist, using technical air in combination with solid insulation or gas mixtures with synthetic substances for insulation. The required insulation strength of natural gases is achieved by a moderate increase of the gas pressure compared to SF_6. Voltages up to 36 kV are commercially available or in the stage of type testing and demonstration at client sites.

In the case of synthetic substances in the gas mix, regular monitoring of gas quality might be required, which is associated with extra maintenance costs due to additional manpower, implementation of procedures and operational costs. However, such monitoring and testing can be easily integrated in existing operation and maintenance schemes. Current breaking is achieved by vacuum circuit breakers which are SF_6-free in both AIS and GIS configurations.

Configuration of substations for primary distribution is planned and implemented on a case by case basis. There are no standard combinations of modules offered and sold in large quantities. Accordingly, there are no large number of variants to be considered when designing, testing, and commercialising new products: the devices are integrated directly into the networks of the final users and, hence, the step of system integration into a distribution kiosk becomes obsolete.

Consequently, the transition to SF_6-free solutions could be relatively fast: for type-tested solutions, a period of 2-3 years appears reasonable. Many SF_6-free solutions are currently at an advanced development stage, thus an extension of available solutions is expected in the medium term.

The costs of upcoming SF_6–free solutions are expected to be equal or just marginally higher than SF_6-containing equipment, at least for some of the products marketed.

2.2.2. Medium voltage switchgear in secondary distribution

GIS arrangement with SF_6 is dominant in secondary distribution due to the numerous constraints associated with secondary distribution (e.g. space, humidity and temperature control) and the technical advantages of SF_6 as an insulating and current breaking medium under such conditions. In the RMU in secondary distribution, AIS does not play a role of importance due to space and environmental constraints in this segment. Moreover, for breaking the standard technology used is load break switch-fuse combination which also contains SF_6.

Technical feasibility and performance of SF_6-free insulation

In the last few years secondary switchgear without SF_6 as an insulation medium, which have the same physical dimensions and electrical ratings as equivalent SF_6 systems of the same manufacturer, have become commercially available. Today a variety of SF_6-free switchgear solutions exist, especially for voltages rated up to 24kV.

In many cases the alternative medium is a gas blend that includes either fluoronitriles or fluoroketones. Some of these solutions use a moderately increased gas pressure to achieve the required insulation strength, comparable to early designs using SF_6. This change is reflected in their structural design to avoid potential pressure losses that would jeopardise functionality. Extensive monitoring during piloting and demonstration indicate that the gas blends do not deteriorate during operation. However, the boiling point and lowest operating temperature for the alternative blends is higher than that of SF_6. Consequently, under the same level of pressure SF_6 switchgear can operate at lower temperatures. Furthermore, blends including fluoronitriles can normally operate at a lower temperature than fluoroketones. Such a limitation can be of practical relevance in applications situated in areas where it can get very cold and where the temperature cannot be controlled.

For voltages up to 12kV some manufacturers also offer solutions with technical air and recently one manufacturer introduced a switchgear with technical air rated up to 24kV. These solutions are not sensitive to the temperature level.

Technical feasibility and performance of SF_6-free breaking

As regards breaking load, break switches with SF_6 are commonly used in secondary distribution. It is a challenge to find cost effective, reliable, and safe SF_6-free replacements for load break switches in secondary distribution because, compared to vacuum circuit breakers, load break switches are normally simpler, cheaper and maintenance free. In particular, the use of circuit breakers will be more expensive and costly due to a need to safeguard the selectivity of the protection system, which ensures that only the faulty part of the system is disconnected rather than the whole system[5]. This may require complex and costly protection coordination between primary and secondary distribution, and potentially between the different operators. Furthermore, with circuit breakers maintenance will normally become necessary, whereas the load break switches are maintenance free. These issues are however of a systemic nature that it is feasible to overcome. Moreover, recently load-break-switch fuse combinations without SF_6 have been introduced.

Costs and market potential

Given the limited range of products currently available on the market and the relatively recent introduction of such products, as well as the many boundary conditions and external factors affecting the final price, it is difficult to gauge precisely the extra investment required by the end-user to purchase switchgear with SF_6-free insulation compared to a unit with SF_6.

Reported extra investment per unit is in the range between 5% to 20%, with some conditional exceptions down to 0% and up to 30%. In addition SF_6-free alternatives may require additional maintenance costs compared to SF_6 products.

[5] This is a challenge is due to the different short circuit clearing times, which are longer in circuit breakers than in load break switch-fuse combinations and sometimes even longer than in the substations circuit breakers.

On the other hand, in addition to the environmental effect, SF_6-free alternatives offer potential advantages:

- the development of smart grids may require frequent reconfiguration of network topologies, e.g. for charging of electric vehicles, and vacuum breakers are more suitable for this purpose;
- the future end-of-life costs for SF_6 recovery, recycling and disposal may be substantial.

Switchgear manufacturers would normally need a certain market perspective in order to make the necessary investment in research, development and innovation required to offer a full portfolio with SF_6-free alternatives.

Furthermore, the introduction of new alternatives in secondary distribution requires a number of steps and is more complex than in primary distribution. Depending on client specification, RMU configuration may vary. Each configuration needs to be type tested. While the volume in secondary distribution is large, the diversity of products is diverse. In some special cases deployment of SF_6-free switchgear may continue to be very difficult, e.g. under extreme environmental conditions or when adding a RMU to an existing secondary distribution network.

For type tested solutions, a period of 2 years transition time is likely to be needed for wider commercialisation. However, tested solutions represent only parts of the total product range. Thus, more time (4 to 5 years) is likely to be needed to satisfy the diversity of client needs, i.e. the portfolio offered to the market will need to grow incrementally. For commercially available solutions some time will be necessary for upscaling the manufacturing capacity.

2.2.3. Generator circuit breakers

In power plants, generator circuit breakers interface the generator with the network, more specifically the medium to high voltage transformer, and they protect both the generator and the transformer. Due to their application, they are designed for extraordinarily high rated and short circuit currents. Because the number of power plants (under construction) is limited, generator circuit breakers represent a niche application and there are very few manufacturers. One manufacturer offers a SF_6-free design, however it is only suitable for a limited range of applications. Other manufacturers do not engage in the development of alternatives. This is not an indication of fundamental technical barriers, simply that the market prospects appear so far to have been too limited to justify development costs.

2.3. Alternatives to SF_6 in higher voltage switchgear

Technical feasibility and performance for SF_6-free insulation

For high voltage substations insulation based on air requires significantly more space than gas insulated configurations. One of the most common AIS arrangements combines air insulated busbars with gas insulated switching devices. Hybrid switchgear combine air insulated busbars with prefabricated modules integrating circuit breakers, disconnectors, earthing switches and instrument transformers in a single, gas insulated housing. Hybrid configurations need less space than AIS but the switchyard[6] is larger than GIS. Solid or liquid media are not used as insulation media in high voltage switchgear

Because of their compactness, completely gas insulated switchgear have been the standard solution for substations in applications where space is critical, e.g. in urban and other densely populated areas or, for example, on high voltage platforms collecting the power of offshore wind farms.

Only gas mixtures are alternatives to $SF_{6;}$ there have been the following recent developments:

- For voltages up to and including 145kV, various SF_6-free GIS designs have been demonstrated and piloted, with manufacturers reporting booked orders worldwide for more than 1 000 bays for the next two years. Depending on the gas blend and associated temperature range, the use case may be restricted to indoor applications. Also, several GIS pilot installations using different gas blends have already been demonstrated for several years.
- For 72.5 kV GIS for offshore wind energy converters, GIS designs exist using blends of natural gases and blends with fluoronitriles, and the products are being manufactured at an industrial scale. Offshore applications imply particular logistic, health and safety challenges, and avoiding SF_6 handling offers advantages in this application.
- For the segment above 145kV, a 170 kV GIS using a gas blend with fluoroketones has been installed in Zurich, Switzerland in 2015. The GIS is based on a 245 kV SF_6 design. Another 170 kV / 50 kA GIS pilot using fluoronitriles is going to be energised in 2020. In this case, physical dimensions are identical to SF_6 designs. A GIS based on natural gases for the rating of 170 kV / 50 kA passed successfully all performance tests.
- Up to 245 kV concept and design studies for SF_6-free switchgear and its components are ongoing. First solutions are expected within a 5 year period.
- For higher voltages (>245kV) substantial R&D is still needed. First commercial solutions relying on gas blends with synthetic substances are expected within a 5 year timeframe. Covering the variety of technical requirements and applications will need more time.

Gas blends based on fluoronitriles and SF_6-based solutions are equivalent in terms of dimensions and electrical ratings. On the other hand, models with gas blends based on fluoroketones and natural gases, require larger physical dimensions compared to SF_6 models with the same power rating. Alternatively, instead of keeping the same power rating and increasing the size of the switchgear, sometimes a lower power rating is sufficient and would allow the use of a SF_6-free system with lower voltage and the same size.

In specific sites where the voltage rate must be maintained and space is restricted, such as substations at power plants or in urban areas, currently designs based on fluoronitriles may be the only viable alternative to SF_6 based switchgear.

[6] "Switchyard" refers to the area where the switchgear is located and its footprint.

In outdoor switchyards, space is less critical as components which have been installed in the 1970s and 1980s have much larger dimensions than modern SF_6 based designs. Replacing them by SF_6-free alternatives of equal ratings will often be possible.

Technical feasibility and performance for SF_6-free switching:

For switching, gas blends and vacuums are already used as alternative to SF_6:

- For voltages up to 145 kV vacuum interrupters are commercially available.
- For voltages up to 170 kV fluoronitrile based blends are commercially available.
- For voltages up to 245 kV concept studies focusing on vacuum interrupters are ongoing
- For higher voltages up to 420 kV series connection of two interrupters are investigated.
- For 420 kV ratings, the EU LIFE programme supports the implementation of a fluoronitrile mixture for a GIS circuit breaker.

Costs and market potential

The larger dimensions of GIS based on fluoroketones and natural gases imply higher costs. Manufacturers indicated a cost factor of up to 200% for alternative GIS being piloted, compared to commercial SF_6-based variants. Simultaneously, they indicated that, as a result of learning curves, reductions in dimensions and thus costs would be possible.

The process of market penetration of alternative solutions for high voltage and extra high voltage switchgear is simpler than in medium voltage. High voltage substations are designed and erected based on customer specifications. The individual configuration is assembled using type tested components.

For clients, the specific environmental, health and safety procedures for alternative gas mixtures have to be implemented in the complete organisation prior to application. For synthetic substances, these procedures are likely to be quite similar to those for SF_6. Nevertheless, dedicated guidelines have to be defined and trainings have to be organised. For alternatives using natural gases only, handling and environmental, health and safety procedures are simpler.

The time needed for the transition to SF_6-free products depend mainly on the voltage:

- Up to 145 kV GIS have been demonstrated with various SF_6-free gas blends; given their advanced stage, commercialisation can be expected within 2 years. A mature portfolio covering all solutions could be available within 5 years;
- Solutions for up to 245 kV are expected to be piloted in the next 2 years and commercial solutions will be introduced in a 5 year timeframe, with full commercialisation taking place later;
- Development of alternatives for higher voltages will take 5 years at least. Progress monitoring is a precondition for defining transitions.

2.4. SF_6 alternatives for equipment related to switchgear

There are a variety of components and devices related to switchgear that currently rely on SF_6. They have in common that no switching is required. In some cases the gas is used as process gas during manufacturing or as insulation only. Some of the components are relevant in medium voltage sector only (capacitors), some applications exist in medium and high voltage.

Instrument transformers for measuring current and / or voltage are used in medium and high voltage. Designs differ per function and voltage level:

- In medium voltage cast resin /epoxy is used as insulator. For part of the product range, SF_6 is used as process gas during manufacturing. The gas can be recycled and circulated in the manufacturing process, and one manufacturer reported a 70% reduction of SF_6 consumption compared to a situation without circulation 20 years ago. Further, limited emission reductions are possible compared to the levels achieved so far. However, the specific reduction costs will be exceedingly high. Only negligible amounts of the gas end up in the product. Other gases and gas blends have been investigated, without satisfactory results. In this application, currently there are no realistic perspectives for complete replacement of SF_6.

- In high voltage, SF_6 has also been used as insulation in the transformers. In some applications, oil is used as insulating medium. Alternative gases consisting of natural substances as well as blends with synthetic substances (fluoroketone, fluoronitrile) are being used. Current transformers relying on alternative gases have been demonstrated for voltages up to 245 kV. Individual voltage transformer designs for voltages up to 420 kV have been presented or are expected to be demonstrated in the next two years. Gas mixtures not using fluoronitriles require higher gas pressure than in the case of SF_6. As a consequence, the size and weight of the housing of alternatives are higher as well. Replacing existing instrument transformers at sites with space limitations, may restrict the range of applicable alternative designs. However, at least in outdoor switchyards, dimensions generally are less critical. The development of mature product portfolios, industrialisation of manufacturing and homologation by end users will take several years, i.e. the set of available alternatives is expected to incrementally grow in the medium term.

Capacitors for medium voltage applications in the lower kV range profit from the dielectric strength of SF_6 and so far no alternatives have been developed. Similar to medium voltage transformers, the gas is used during manufacturing. Negligible portions are encapsulated in the component. So far, practically they cannot be recovered and SF_6 will be released at disposal at the end of life.

Bushings are used to insulate conductors entering a device from the enclosure. In bushings oil insulated paper (OIP), resin insulated paper (RIP) and resin insulated synthetics (RIS) coexist with SF_6 based designs. For voltages below 145 kV, designs based on alternative gas blends are available. Manufacturers indicate that with ongoing efforts a gradual extension of the voltage ranges up to 245 kV is realistic in the next couple of years. However required R&D investments are substantial. Lifetime tests of reasonable duration are a precondition for commercial rollout. At the end of life, the gas can be recovered and processed. Some designs, though, use the insulation medium in combination with foams. In this case, recovery of the gas is complicated and respective processes are not in place. In practice, currently the gas will be released after disposal at the end of life[7].

Gas insulated lines and gas insulated busbars and busducts are used for compact, high power transmission over limited distances, close to power plants and substations. Since 2017 SF_6-free designs based on gas blends with fluoronitriles have been demonstrated successfully for voltages up to 420 kV. A system based on fluoroketones will be delivered in 2020 and will go into operation in 2021. Also, a 420 kV pilot based on compressed air will be implemented in the same period. At the end of life, synthetic gases and decomposition products can be recovered and processed. In the case of natural gases the gas can be released to the atmosphere, which would reduce the overall transportation and recycling processes.

3. Conclusions

On the basis of the above, the following can be concluded as regards **new medium voltage switchgear used in secondary distribution**.

For this segment SF_6 is currently the dominant technology for both insulation and breaking. Commercial alternatives for insulation have recently become commercially available for certain applications for up to 24 kV. Their technical characteristics, like physical dimensions, technical life and reliability are apparently identical to equivalent solutions of the same manufacturers using SF_6. However, it will take time for manufactures to develop the full product range and build up the needed production capacity to serve the full market. The different types of switchgear in the product range could become available in around 2 to 5 years, depending on how advanced the development and testing is for each type. However, in some special cases, it may still remain difficult to replace SF_6 e.g. due to special space requirements or environmental conditions. The additional costs per unit are likely to be 5% to 30% higher, even after industrialisation and upscaling of production.

As regards breaking, vacuum circuit breakers are the most common alternatives to SF_6-containing load break switches. It is technically feasible to use vacuum circuit breakers but the main obstacles to a wider uptake in secondary distribution are the need for maintenance and the complex and costly changes that would be required to mitigate the risk of compromising the selectivity of the protection system, which ensures that only the relevant part disconnects in the case of a fault. Recently, SF6 free load break switches, that are not having such systemic barriers have been presented.

Clearly, it will be easier to install SF_6-free equipment in “greenfield” situations or complete replacement (exchange of an existing distribution cabinet at the end of its life) rather than during partial retrofits or extensions where a combination of SF_6 and SF_6-free equipment coexist in a substation.

The report also assessed the feasibility of replacing SF_6 in **new medium voltage primary distribution**. In this segment SF_6-free alternatives have always been available and a growing number of SF_6-free switchgear solutions are being developed and offered by manufacturers.

[7] For that reason, in Germany, banked SF_6 is accounted as emissions during production.

Characteristics, like physical dimensions, technical life and reliability are apparently identical to the equivalent solutions of the same manufacturers using SF_6. After full market deployment, only marginal additional costs are expected, because the designs of alternatives are very similar to products using SF_6. Full commercialisation of alternative solutions after a transitional period of 2 or 3 years seems to be realistic. Breaking is not an issue in primary distribution as vacuum circuit breakers are already common.

With regards to **higher voltages,** GIS up to 145kV have been demonstrated with various SF_6-free gas blends. Commercialisation can be expected within 2 years for these types of systems, and a mature portfolio covering all systems may become available within 5 years. Solutions for up to 245 kV will be piloted in the next 2 years and commercial solutions are likely to be introduced in a 5 year timeframe with full commercialisation later. Development of alternatives for higher voltages may take 5 years at least. In space restricted environments, GIS designs based on fluoronitriles may be the only alternative to SF_6 because other solutions require more space. For most applications, however, this is not limiting.

SF_6 is used as process gas in the manufacturing of **medium voltage instrument transformers and capacitors**. So far, potential alternatives do not deliver satisfactory results. For minimising emissions during manufacturing, good housekeeping and effective reuse of the gas are essential. Product emissions during operations and disposal are negligible. For **bushing** and for **gas insulated lines** and **gas insulated busbars** and **busducts,** for certain voltage ranges, penetration of alternatives could become relatively high in a 5 year timeframe.

In general, where the SF_6-free alternatives are more costly than switchgear containing SF_6, policy intervention is likely to be needed to trigger a transition. As part of the European Green Deal, the Commission has recently launched a review of the EU rules on fluorinated gases including the evaluation and proposal to revise the F-gas Regulation in Q4 2021.[8] The findings in this report will serve as a technical input to that review.

[8] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12479-Review-of-EU-rules-on-fluorinated-greenhouse-gases