SF_6 Emissions from a National Population of High-Voltage Switchgear

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Twenty years of careful recordings of SF_6 inventories and emissions from a large switchgear population show that by implementing appropriate measures annual emission rates as low as 0.2% can be achieved.

Introduction

Sulfur hexafluoride (SF_6) has since around 1960 been extensively and increasingly used as an insulating and current interrupting medium in high-voltage switchgear. Its physical properties are excellent for this application and superior to the mineral oil and compressed air applied in earlier switchgear technologies. However, around 1990 it became widely recognized that when released to the atmosphere, SF_6 is an extremely potent greenhouse gas. A growing concern over climate changes has led to searches for alternatives to SF_6-based switchgears [1]–[3], and various new concepts are now entering the market [4].

Switchgear and substations are—like most high-voltage equipment—built to last, and service lives of 50 years are not unusual. Consequently, many of the SF_6-containg components put into service towards the end of the last century are likely to remain in operation for many years to come [5], [6]. Ensuring that the SF_6 emissions from these installations are low and under control has become an important issue.

However, obtaining accurate numbers for SF_6 inventories and emissions has in many cases proven difficult, due to:

- Legacy equipment without nameplate data on installed SF_6 capacity.
- Large volumes of SF_6 in gas insulated switchgear (GIS) where data is not available for the individual compartments.
- Lack of monitoring or measurements in practice, employing a repair procedure to "keep the lights on" without specific consideration for refill quantities.
- Lack of regular maintenance check for leakages.
- Lack of reporting and focused attention for immediate leak repair resulting in higher leak volumes.

In many countries the authorities require users of SF_6 to report their inventories and emissions annually [7]. Even though regulations were implemented several years ago, the reporting in many cases remains incomplete and inaccurate. This is presumably partly because the information is not always easily accessible as mentioned above, and partly because suitable nationwide reporting systems are not in place or are not being used by all.

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Reporting from the so-called EU-28 (European Union member states plus Bulgaria, Croatia and Romania) to the United Nations Framework Convention on Climate Change (UNFCCC) implies an SF_6 emission rate for high-voltage equipment in service of 0.57% (annual emissions divided by the amount installed), according to a careful review of the data for 2017 by Billen et al. [8]. Moreover, the same authors state that the UNFCCC inventory and emissions data [9] are not consistent with models [10], [11] based on the measured atmospheric concentrations of SF_6. These suggest annual emissions of 1.3% for the EU-28 in 2017. An extensive comparison between the UNFCCC-reported emissions and atmospheric concentrations also suggests a significant global underreporting of the SF_6-emissons [12].

In the USA the Environmental Protection Agency (EPA) and the electric power industry established in 1999 a collaborative SF_6 emission reduction partnership. For 2020 the participating utilities reported an emission rate of 1% [12]. However, about one third of US utilities (as measured by transmission line lengths; a known quantity) are not members of the EPA partnership, and their estimated contribution to the total "are a significant source of uncertainty" [12]. The total SF_6 emissions in 2020 from the US electric power system is estimated at 3.3 MMT CO2 Eq. (million metric tons CO_2 equivalents), corresponding to approximately 130 metric tons of SF_6. The installed amount (termed "total industry nameplate capacity" in [12]) of SF_6 in the US electric power system was 156.5 MMT CO_2 Eq. in 2016. Assuming only a minor change in this parameter between 2016 and 2020 the overall emission rate can thus be calculated to somewhat above 2% in 2020.

Data collected from all three transmission system operators (TSOs) in Great Britain from 2010 to 2016 showed an average emission rate of 1.3% [13]. There were substantial fluctuations from year to year, and even greater differences between the three TSOs. The latter suggests that emission rates depend on several TSO-specific factors such as age of switchgear population, preferred technology (gas insulated switchgear (GIS) vs. air insulated switchgear (AIS)), maintenance practices, share of the equipment installed indoor vs. outdoor and thereby more exposed to the environment, etc.

In Norway, the authorities around the turn of the century considered introducing a heavy taxation on SF_6 unless emissions were curbed. The utilities then started improving their operation, maintenance and repair processes with the objective of reducing emissions. In parallel, a national GIS User Group has, since 2003, gathered quite detailed information about the domestic SF_6 usage and emissions. This has yielded trustworthy, high-quality emission data on a national scale for transmission and sub-transmission level switchgears, at least for the recent years. In contrast to some of the surveys referred to above, the SF_6 emissions are here determined from actual measurements on switchgear; they are not based on estimates of questionable precisions.

This paper presents SF_6 emission rates from the Norwegian GIS and AIS populations rated for 145 kV and above. Initially, the processes that were implemented to reduce the emissions, and to how data on SF_6 inventory and emissions have been gathered, are reviewed.

Process Improvements

Reducing the Emissions

Several efforts aiming at reducing the SF_6 emissions were initiated around 2003 and gradually intensified and expanded in the years after. The most important equipment modifications and improvements are described below.

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- The electric utilities invested in modern SF_6 handling equipment, including vacuum pumps that made it possible to reclaim nearly all the gas before opening the switchgear for maintenance or repair. Most older gas carts could not retrieve gas below atmospheric pressure, resulting in large emissions when doing invasive work.
- Some first-generation GIS came without manometers, but only equipped with a simple arrangement that gave a signal when the pressure had dropped 10% below the filling pressure. More accurate pressure surveillance was implemented, either by installing permanent manometers on all compartments or by periodically measuring the pressure in each compartment with a portable manometer.
- Some old GIS had external piping that connected several gas compartments. This reduces the number of manometers needed and allows for gas to flow between compartments and replenish gas in a leaking compartment from others that does not leak. The obvious drawback is that it takes longer before a leak can be detected, resulting in larger emissions. By removing the external piping and installing manometers on each gas compartment, leaks became detectable much earlier.
- Another approach implemented to reduce the size of large gas compartments of first-generation GIS—especially at the 420 kV level—was to replace some of the non-gas tight epoxy insulators or spacers that holds the high voltage conductor, with the gas-tight version.
- Currently, equipment for on-line monitoring of the SF_6 pressure in all gas compartments is being installed on a few GIS. Careful pressure trending and surveillance are expected to allow for even earlier detection of leaks compared to conventional periodic manometer readings.

Equally important as the various technical improvements are the changes in the procedures and policies for operation and maintenance of SF_6 switchgear that were implemented. As outlined below, the changes affect the company management, the system operators, and the technicians that do the practical work.

- Maintenance crews have been educated and trained in gas handling, and procedures are formalized and improved. As late as in the 1990s, the common practice during planned maintenance of switchgears containing moderate amounts of SF_6, (e.g., 145 kV breakers in air insulated substations) was in some utilities to start by deliberately discharging the gas. Stricter procedures forbid this and have made reclaiming the SF_6 mandatory.
- A European Union regulation from 2006 established requirements and made certification mandatory for personnel recovering SF_6 from high voltage switchgear [14]. Since then, more than 500 individuals from Norwegian utilities and industry are certified after having followed a two-day theoretical and practical course and passing an exam. Hence, the knowledge about SF_6 and SF_6 handling, such as its effect on global warming and how to reduce emissions when doing work on switchgear, has obviously improved greatly among utility personnel.
- Sufficient time is allocated for gas handling during invasive switchgear maintenance and repair. Although it means increasing outage times, it is acknowledged by system operators and asset managers that properly reclaiming the SF_6 not only requires gas handling equipment with a sufficiently large pumping and storage capacity, but also enough time. This is particularly the case when doing work on large GIS.
- The utilities have implemented procedures where manometers are checked periodically by the station maintenance personnel, typically every two or three months. Most attention is paid to the GIS due to their large SF_6 volumes.

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- The general policy among the switchgear owners concerning SF_6 leaks has become stricter. For example, the utility with by far the largest SF_6 inventory has implemented a policy where even small leaks are not acceptable and should be repaired as soon as possible. This may require deenergizing an entire GIS, in some cases with major consequences for the system operation. Such difficult trade-offs are left to top management to deal with.

Although there are certainly variations in how the several dozen electric utilities and industrial companies that have SF_6 equipment are operating, it is generally recognized and accepted that reducing emissions means implementing costly, complicated and time-consuming efforts such as those described above.

Collecting inventory and Emission Data

As mentioned above, the collection of SF_6 inventory and emission data was initiated in 2003, but the utilities spent several years establishing good procedures and systems for their "SF_6 book-keeping". A complicating factor was that information about SF_6 volumes or masses in the GIS installed decades earlier in most cases was unavailable. The nameplates typically only provided pressure values, the GIS vendors did not know, so the utilities were left to determine the SF_6 quantities by means of whatever drawings they had available and/or by measuring the physical dimensions of the GIS compartments, a complicated and time-consuming effort.

Consequently, it took some work and several years after 2003 before SF_6 inventory and emissions data for the GIS were complete and of a decent quality. To some extent this also applies to the AIS equipment. This article only considers data collected from 2012 and onwards to avoid presenting inaccurate or questionable information.

The procedures each utility applies for keeping track of their SF_6 inventory and emission vary, but all members of the GIS User Group are obliged to at least once a year fill in updated data into a web-based reporting system. This system was established by the user group, and the information is aggregated and forwarded to the authorities, and eventually becomes a part of the national statistics on greenhouse gas emissions.

When the utilities report an SF_6 emission it must be categorized as either:

- L*eakage:* a leakage that has occurred over time,
- *Repair:* a loss during repair / unplanned maintenance,
- *Maintenance:* a loss during planned maintenance, or
- *Failure:* a gas discharge caused by a sudden component failure.

Reported emission data are the amounts of SF_6 required to replace or top-up the switchgear to the specified pressure as read from the temperature compensated pressure gauges that are installed on the GIS compartment or the circuit breaker in question. Losses caused by accidental mishandling of the gas handling equipment are included.

GIS and AIS Populations Included in the Study

As of 2022 there are 180 GIS filled with SF_6 (in addition to a few with other gases) operated by the members of the GIS User Group in the Norwegian 145, 300 and 420-kV networks. A handful of small

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145-kV GIS are owned by companies that are not members of the GIS User Group are not covered. A few SF_6-insulated instrument transformers have been in operation in air insulated substations for parts of the considered period, but their contributions to SF_6 inventory and emissions are not included.

Fig. 1 shows the distribution in age and voltage level of the considered GIS population, counted as number of circuit breakers and year of installation. As can be seen, a large portion of the 300-kV and 420-kV GIS are quite old as they were installed in the late 1970s and early 1980s. After 1990 most of the expansion has come in the 145-kV system. The average age is at present (2022) 17, 37 and 29 years for the 145-kV, 300-kV and 420-kV GIS, respectively, and they include in total 1,004 circuit breakers. Only eight GIS have been decommissioned.

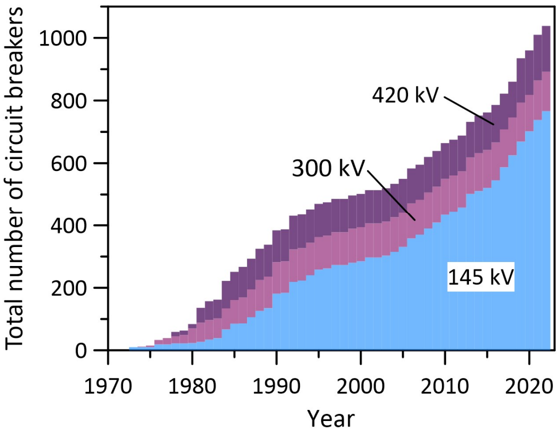

Figure 1. Accumulated number of SF_6 circuit breakers in operation in GIS in the Norwegian transmission and sub-transmission systems.

In contrast to most other countries, all GIS in Norway are installed indoors, making them less exposed to corrosion, large temperature variations and other environmental stresses that over time tend to increase leak rates.

Concerning the SF_6-containing AIS population for 145 kV and above, the available information about the switchgear's number, voltage ratings and age is not as detailed as for the GIS. The ratio between the number of AIS and GIS circuit breakers is approximately 3:1, and their age distributions are not believed to differ much. The vast majority of AIS equipment at the considered voltage levels are installed outdoor, in several cases in a rather harsh climate.

The amount of SF_6 in use in the considered populations from 2012 to 2021 is shown in Fig. 2. In 2021 the GIS held approximately 236 metric tons of gas and the AIS approximately 58 metric tons. Hence, approximately 80% of the SF_6 is found in 180 GIS having around 1,000 circuit breakers, and 20% in around 3,000 circuit breakers in air insulated substations.

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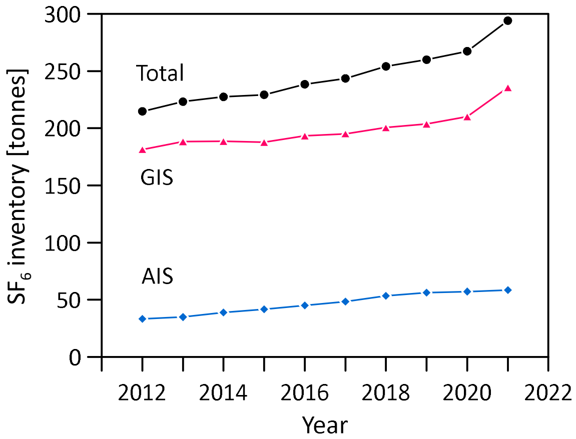

Figure 2. Amount of SF_6 used in GIS and AIS in operation in the Norwegian 145, 300 and 420-kV systems.

First generation GIS contains proportionally far more gas than those being installed during the last 20 years as they are based and on larger and less efficient designs [15]. Hence, the increase in the SF_6 inventory over the years is less than Fig. 1 may suggest. Design improvements have reduced the gas volumes significantly; for one manufacturer the amount of SF_6 per 145-kV circuit breaker bay in the GIS currently offered is only around 20% of that of their first-generation models.

All switchgears, both GIS and AIS (with a very few exceptions), are designed and manufactured in Western Europe, and all the major vendors are represented in the studied population.

SF_6 Emissions

Annual Emission Rates

Fig. 3 shows the recorded annual SF_6 emissions. For GIS all emissions are included, for equipment in air insulated substations only emissions from the circuit breakers are covered.

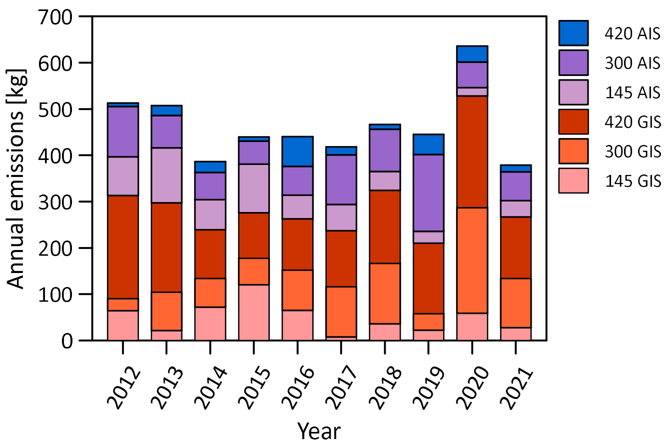

Figure 3. Annual SF_6 emissions (in kilograms) from switchgears in the Norwegian 145, 300 and 420-kV systems.

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As can be seen, the total amount of SF_6 released to the atmosphere from all substations rated for 145 kV and above shows variations from year to year over this ten-year period, from a little under 400 kg to somewhat above 600 kg per year. Of the recorded total emissions over the 10-year period of 4,629 kg, approximately two thirds came from GIS and one third from AIS.

The 45 GIS operating in the 300-kV and 420-kV systems are the largest sources for SF_6 emissions. They account for 53% of the total in the considered 10-year period. The 135 145-kV GIS have comparably lower emissions, presumably because they contain less gas per circuit breaker bay and because most of them are relatively new.

Regarding AIS, the 300-kV equipment in most years show considerably higher emissions (in kilograms) than their 420-kV counterparts. The number of circuit breakers is roughly the same at these voltage levels, but the age distribution differs substantially. The 300-kV AIS are in average approximately twice as old, and corrosion in flanges and degrading polymer and O-ring seals cause the older equipment to leak more.

The most interesting quantity, however, is the annual SF_6 emission rate, i.e., the amount emitted during a year divided by the amount installed in the equipment in service that year. Fig. 4 shows this percentage for GIS and AIS separately, and the overall, national level rate.

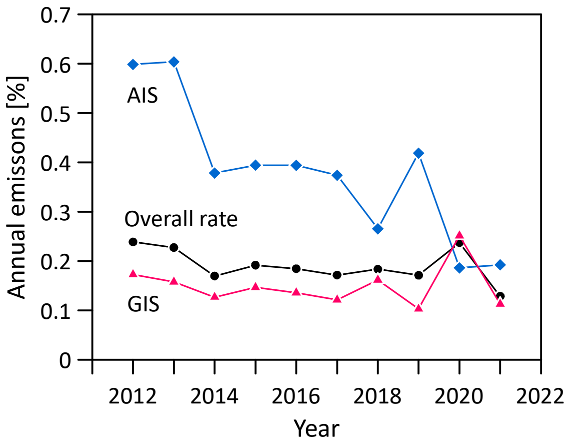

Figure 4. Annual SF_6 emissions rates (in percentage of inventory) for the period 2012–2021.

The overall annual emission rate is for most of the years around 0.2%, and shows a slowly decreasing trend, with the year 2020 being an outlier.

A second observation is that the emission rate for AIS is considerably higher than for GIS, but the difference is becoming smaller over time. For the last couple of years, the rates are quite similar. A possible explanation is that extensive replacement and investment programs of AIS in the 300 and 420-kV grids in this period brought in newer switchgears that have lower leakage rates.

Cause of Emissions

Fig. 5 shows the cause of the reported emissions, both for GIS and AIS.

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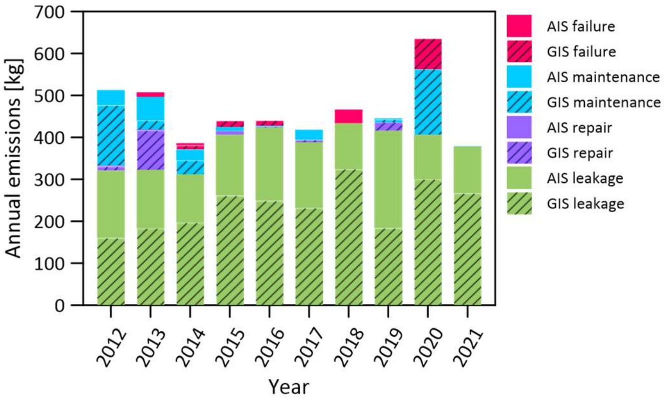

Figure 5. Cause of the SF_6 emissions (see text for explanations).

Approximately 82% of the released SF_6 was categorized as leaks during normal service. Considering that there are four times as much SF_6 in the GIS as in the AIS of this population, it is somewhat surprising that the difference in amount of gas leaked is not larger. The larger gas volumes in GIS make leak detection alarms activate after release of more gas. On the other hand, this may also cause leakage in GIS to receive more attention, and the switchgear owners may be more determined to quickly stop leakages in GIS than in AIS. Moreover, the environmental stresses on polymer O-rings, seals and gaskets may be more severe for the outdoor AIS than for the indoor GIS.

The large emissions attributed to GIS maintenance in 2012 and 2020 can—at least in part—be explained by that several large 300 and 420-kV GIS went through a full overhaul these years. However, the emissions are not a result of poor gas handling during this work. In several cases it was found that the amount of SF_6 retrieved before opening was not enough to fill up the same gas compartments to their rated pressure afterwards, even though all the SF_6 had been carefully recovered. Hence, small leaks occurring over years and even decades prior to the revisions are probably accounting for a substantial portion of the SF_6 emissions registered under "GIS maintenance" in Fig. 5. This experience clearly demonstrates how difficult it is to precisely identify the cause of SF_6 emissions from switchgears.

The same may apply for the nearly 100 kg of emissions recorded as "GIS repair" in 2013. Several failures in 420-kV GIS occurred this year, and extensive repair works were necessary, including evacuating and backfilling large gas compartments. Again, topping up with new SF_6 afterwards to compensate for small, unnoticed leaks over the previous years may account for a substantial portion of the recorded emission.

In 2020 two internal arcing failures where the over-pressure relief system (the "burst discs") activated in one 300 and one 420-kV GIS caused large amounts of SF_6 to be released; in one of the cases almost 60 kg. This demonstrates that single incidents may have a significant effect on the annual SF_6 emission rates, even on this national scale.

Discussion

Obtaining trustworthy and accurate SF_6 emission data from components that have low leak rates—which is the case for most switchgears—takes years of careful pressure monitoring and precise recordings of any gas top-ups. Especially old GIS at the higher voltages where the gas compartments are large, but their sizes are not exactly known, are a challenge in this regard. The approach reported on here is probably the only viable one when dealing with a national population consisting of GIS and AIS of a multitude of makes, models and vintages. Clearly, the quality of the data relies heavily on those responsible for the day-to-day operation of the switchgears and careful follow-up over many years, paying attention to details.

Two factors are assumed to be particularly important in giving credibility to the emission rates reported here. First, the existence of a GIS User Group with a good coverage and a high standing among the utilities and industries has made it possible to organize the collection of SF_6 inventory and emission data from many contributors in a coherent and efficient way.

Second, by not including the information from 2003–2011 in the analyses, the consequences of slow starts, initial difficulties, unclear responsibilities, and other shortcomings associated with such a comprehensive gathering of information are presumably greatly reduced. By 2012 routines and procedures for collecting and submitting the requested data were well established among the utilities, causing them to provide good quality data.

There are of course cases where emissions have not been reported, incorrect estimates of inventories, and other flaws in the submitted information. Still however, it is assumed that the quality of the data is as good as can be realistically achieved on a national level, considering the variety of SF_6 switchgears and the many parties involved.

The overall annual SF_6-emission rate is determined to approximately 0.2% and is—at least in the last couple of years covered by this survey—the same for GIS and AIS. This is far lower than what other studies have found, although their scopes and methods may have been different. But again, the quality of the emission data reported on here is deemed good, because they are collected in a way that makes them more reliable than most others.

Reducing the annual SF_6 emissions from the considered switchgear population significantly below the 0.2% level would probably require even costlier measures. The type test requirements that the oldest switchgears had to comply with, was an annual leakage rate of less than 1%. As shown in Fig. 5, most of the SF_6 released from switchgears are caused by leaks, probably typically as small amounts of gas emitted from many gas compartments over many years. This is not easily corrected.

It has been proposed to detect leaks by adding sensors that continuously monitor the SF_6 density in each gas compartment [16]. With accurate density measurements and active trending, leaks can be detected long before the pressure drops to the level where the conventional temperature compensated pressure gauges give a signal as a reactive loss of pressure. However, installing such a system, including data storing and processing capabilities, is a significant investment.

New SF_6 switchgears are typically specified with an annual leak rate of 0.1%. Hence, as older equipment gradually is decommissioned and replaced, lower SF_6 emission rates are expected. Even more so if the new switchgears are based on SF_6-free technology. Stricter regulations and even banning the use of SF_6 in some applications are to be enforced to foster such a development [17]. The EU Taxonomy requires overview of, among many other things, emissions and also "pushes" the industry to become more sustainable [18].

Given the lifetime of 40–50 years for SF_6 switchgear, any equipment in operation today will be in service for decades to come. It is vitally important to ensure that they are operated and maintained in ways that minimize the release of SF_6 to the atmosphere.

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Conclusion

The annual SF_6 emissions from a population consisting of almost all switchgears in the Norwegian 145, 300 and 420-kV systems are in the ten-year period from 2012 to 2021 found to be around 0.2% of the amount in use, far less than reported in other investigations of SF_6 emissions.

This comes as a result of a coordinated and sustained national effort involving upskilling, using the latest technology for gas handling, new procedures and increased attention, etc. It is assumed to be about as low as can be realistically achieved with mixed a GIS/AIS population consisting of equipment of different ages, models and manufacturers.

More than 80% of the SF_6 release was caused by small leaks, many of these going unnoticed for years. The rest were due to sudden discharge of SF_6 during failures, and gas loss during planned and unplanned maintenance and repair that involve recovery and backfilling of gas.

AIS had a higher emission percentage than GIS in the first years covered by the survey, but their rates became about the same in 2020 and 2021.

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