
# Assessment of the potential to reduce UK F-gas emissions beyond the ambition of the F-gas Regulation and Kigali Amendment

Final Report

Report for Committee on Climate Change

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# Executive Summary

**Context to the study**

Work done under this contract has helped to generate the evidence base that the Committee on Climate Change (CCC) needs for its analysis of optimal pathways to help the UK achieve its carbon budgets and the 2050 target under the Climate Change Act.

The CCC scenarios for meeting the fifth carbon budget set out a 68% cut in F-gas emissions from 2015 to 2030, involving reductions in emissions from refrigeration, air conditioning in buildings and vehicles and aerosols. However, the evidence base in this area is old. This has limited the CCC's ability to assess whether there is potential for the Government to implement policy that goes beyond the existing EU F-gas Regulation. This project answers the question about what opportunities there are to go beyond the EU regulatory minimums on F-gases, and, in which sectors the greatest opportunities lie with the greatest certainties of achieving reliable reductions.

**Historical F-gas inventory and projections**

The refrigeration and air conditioning sector (RAC) is currently the largest of the F-gas emitting sectors. With the addition of heat pumps (HP), the sector is referred to as the RACHP sector although currently the emissions from heat pumps are a very small component of the total emissions from the sector. Future government energy efficiency measures include heat pumps, so it was important to explicitly include this sector in our assessment.

Estimates of historical and projected emissions from the refrigeration and air conditioning sectors are derived from the BEIS F-gas emissions and projections model. In 2016, total emissions are dominated by emissions from refrigeration, air conditioning, and heat pumps. The GWP weighted F-gas emissions in 2016 are approximately 3% of net national GHG emissions.

Total emissions of F-gases are predicted to decline strongly from 2016 to 2032. The relative importance of each market sector changes between the latest year of the historical emissions, 2016, and 2032 which is the last year of the 5$^{th}$ carbon budget. Emissions from the RACHP sector dominate total F-gas emissions, on a GWP weighted basis, in both 2016 and 2032. But by 2032, metered dose inhalers and gas insulated switchgear have become a much greater fraction of the sector total emissions. The relative importance of foams is predicted to grow, but where foams are used in building insulation, this is an application where recovery of the blowing agents used at the end of life is difficult because separation of the foam from the associated building material is technically extremely difficult.

**Initial estimates of future potential for emission reductions**

The F-Gas Regulation already creates big cuts in emissions – there is a 79% phase-down for HFCs, which are the dominant F-Gas in the UK inventory. Under the current EU F-Gas Regulation, the UK should cut emissions from approximately 16.0 to 3.5 Mt $CO_2$ eq. The analysis in this work shows there is potential to reduce the residual 3.5 Mt $CO_2$ eq. further by introducing a more ambitious set of targets.

The initial key sectors identified as being worth investigating for future further mitigation actions to reduce emissions further were:

- Refrigeration Air Conditioning and Heat Pumps (RACHP)
- Metered Dose Inhalers (MDIs)
- Gas Insulated Switchgear (GIS).

In most sectors, further reductions in emissions were quickly assessed to be likely to be difficult or are technically difficult to achieve. These sectors include: technical aerosols, foams, semiconductors, Airborne Warning and Control System (AWACs), solvents, and fugitive emissions from aluminium production. During this project, effort was concentrated in the sectors which have the greatest likelihood of delivering reductions in F-gas emissions.

**Enhanced mitigation options in Refrigeration, Air-conditioning and Heat Pumps (RACHP)**

The RACHP sector is the UK's main user and emitter of HFCs. Since the phase-out of ozone depleting refrigerants (CFCs and HCFCs), HFCs have become the main refrigerants used in a wide range of RACHP applications. It is important to recognise that the RACHP market is highly complex, with many different market sectors and sub-sectors. This leads to the need for a range of different refrigerants that are designed to suit specific applications. Some parts of the RACHP market have been using non-HFC refrigerants for many years. In particular, domestic refrigerators have been using a hydrocarbon on a large scale in the UK since the early 2000s and large industrial systems often use ammonia.

The 2014 EU F-Gas Regulation significantly affects the use of HFCs in RACHP systems. The HFC phase-down process will lead to a 79% cut in the GWP weighted quantity of HFCs that can be sold in the EU by 2030. Significant cuts are already in place – in 2018 the cut is 37% from the baseline.

In 2016 it was estimated that UK F-Gas emissions from RACHP were 12.6 million tonnes $CO_2$ equivalent. This was approximately 78% of total UK F-Gas emissions in 2016.

The F-Gas Regulation is expected to reduce RACHP F-Gas emissions by 84% between 2016 and 2032. This is a significantly different characteristic to other sectors that are the focus of this study (MDIs and GIS). The use of HFCs for MDIs are not controlled by the F-Gas Regulation and the use of $SF_6$ in GIS is only constrained by rules on leak prevention, mandatory leak testing, refrigerant recovery and technician training. However, despite the significant F-gas emission reductions that are expected from RACHP under the current Regulation, there may be further opportunities to reduce emissions to an even lower level and/or to bring down emissions more quickly.

RACHP emissions are expected to fall from 12.6 million tonnes $CO_2$ equivalent in 2016 to 2.0 MT $CO_2$ in 2032 (a 84% cut from 2016) and 0.8 MT $CO_2$ in 2050 (a 94% cut from 2016). The analysis in this project shows that to reduce the residual amount of HFC consumption post-2040, the sector of greatest importance is stationary air-conditioning. There is also some potential for reducing emissions from heat pumps and commercial / industrial refrigeration. The reason that these sectors remain reliant on HFCs is related to the availability of a refrigerant suited to the specific applications. The sectors where further future emission reductions are "difficult" are medium size air conditioning with refrigerant of charges of approximately 10 to 50 kg and retail refrigeration with refrigerant of charges of 5 to 20 kg.

There is predicted to be a gradual drop in RACHP HFC emissions between now and the late 2030s. This decline is mainly driven by the gradual switch away from high GWP refrigerants in new equipment. The rate of switching is constrained mainly by the lifecycle of existing RACHP equipment. In most RACHP market sectors there are already lower GWP alternatives available. In the small-medium building air-conditioning market, ultra-low-GWP (with a GWP <10) non-flammable replacement refrigerants are not available at present and industry has not started to develop these refrigerants. However, experience in the car air-conditioning market suggests that there could be potential to develop these alternative refrigerants.

This work has identified 6 main RACHP emission reduction options or measures beyond current policy forecasts, the implications of which are described in section 3.5. After energy savings are accounted for, we believe that in addition to the additional emissions savings from reduced energy requirements, some of the 6 measures could have a cost benefit. The energy savings that might accrue are greater than costs (see page 28 of this report, and see also Table 3-6 on page 31). Cost data are available in Section 3.5.1 and Table 3-6.

**Enhanced mitigation options for Metered Dose Inhalers (MDIs)**

MDIs are medical aerosols used for administering certain drugs directly into a patient's lungs. They were first introduced in the 1950s and are widely used globally for the treatment of various lung diseases, in particular asthma and COPD (chronic obstructive pulmonary disease). MDIs used CFC propellants until the phase-out of CFCs that started in the 1990s. The CFC propellants were replaced with HFCs – mainly HFC-134a and some HFC-227ea. The replacement process was lengthy and expensive. The switch from CFCs to HFCs took over 10 years to achieve and MDIs were given special exemptions during the phase-out of CFCs under the Montreal Protocol. HFCs have been used in all MDIs sold in the UK and most developed countries since 2009. Progress with CFC propellant phase-out has been slower in developing countries, with the final phase-out of CFC MDIs in around 2016. It is worth noting that for most other EU countries, MDI usage is much lower than in the UK, hence emissions from MDIs will form a much smaller part of the total F-Gas emissions. This might mean that there could be less enthusiasm at EU level for changes to the regulatory regime..

In 2016 it was estimated that UK F-Gas emissions from MDIs were 1.0 million tonnes $CO_2$ equivalent. This was approximately 6% of total UK F-Gas emissions in 2016.

The current EU F-Gas Regulation exempts MDIs from the EU HFC phase-down, hence there are no direct regulatory pressures on this application of HFCs. The use of MDIs has risen steadily over recent years. Around 40 million MDIs were prescribed in the UK in 2006, rising by 35% to reach the level of 54 million in 2016. This increase is at a considerably higher rate than the growth in population, which rose by 8% during the same period. A conservative estimate is a further 10% rise of MDI use by 2030, leading to a projected emission of 1.1 MT $CO_2$eq. It is forecast that MDIs will represent over 25% of UK F-Gas emissions during the $5^{th}$ carbon budget period under current policy.

The two main GHG mitigation options available are: 1) Dry powder inhalers (DPIs), a not-in-kind alternative to MDIs, and, 2) MDIs using a low GWP propellant. There are low GWP alternatives that could replace a significant proportion of current MDI HFC propellant usage and have the potential to cut emissions by over 90% by the $5^{th}$ carbon budget period. The main barriers to a greater uptake of DPIs are (a) perceived cost issues and (b) lack of awareness amongst GPs and patients. If these barriers could be overcome, DPIs could take a significant share of the current MDI market well before 2028. The main barriers to the uptake of low GWP propellants are (a) the cost of product development and (b) the lengthy timescale before new products are likely to be fully approved. Whilst DPIs could replace MDIs used in the UK quite quickly, perhaps over a 3 to 5 year period, the introduction of low GWP propellants is likely to take a further 6 to 10 years. By the start of the $5^{th}$ carbon budget period in 2028 a transition to either of these options could be complete.

Based on the research carried out during this project it is believed that there is an important role for both technologies. The development of the markets for both DPIs and low GWP MDIs should be encouraged to maximise the availability of effective treatments that suit the whole patient population. By the end of the $5^{th}$ carbon budget period the annual emission reduction is 1.0 million tonnes $CO_2$. The cumulative reductions from 2020 to 2032, compared to business-as-usual is estimated to be 9.4 million tonnes $CO_{2eq}$.

It is likely that a dual strategy is required, with much more widespread use of DPIs and the introduction of low GWP MDIs. This maximises patient options in the future and may help minimise the total cost of abatement. For each of the major applicable medications, either a switch to low GWP MDIs or to DPIs should have costs in the range £0 to £20 per tonne $CO_2$ saved.

**Enhanced mitigation options for Gas Insulated Switchgear (GIS)**

Gas insulated switchgear (GIS) and Gas Insulated Lines (GIL) are used in the transmission and distribution of electricity. A gas is used to insulate high voltage components including bus-bars and switching equipment (interrupters). Since the 1970s, the gas used for GIS applications has been $SF_6$ (sulphur hexafluoride). This molecule has excellent electrical properties at the extremely high voltages encountered in electricity transmission systems and allows the use of compact and cost-effective switchgear. A key drawback in the use of $SF_6$ is that it is an extremely potent greenhouse gas with a GWP of 22,800. GIS using $SF_6$ was first introduced in the UK about 40 to 50 years ago. Prior to that high-pressure air insulated switchgear and oil filled switchgear were used but this equipment is physically much larger than $SF_6$ devices and would be very expensive now. GIS equipment is usually used for very long periods. Indoor GIS can last 50 years and outdoor GIS 35 to 40 years and this means that the existing bank of $SF_6$ equipment will be in use for a considerable period of time until it is replaced.

There are important technology differences between GIS used in transmission and distribution: transmission is the high voltage network that carries electricity over long distances from power stations to lower voltage local networks; distribution is the lower voltage network serving individual end users. The types of GIS required in transmission and distribution are different. It is easier to insulate switchgear at lower voltages and distribution GIS tends to be small hermetically sealed units, with almost zero leakage. Transmission GIS units are much larger and have gasketed joints which do suffer from a small level of leakage.

There have been significant improvements in gas management by transmission and distribution companies since the 2006 F-Gas Regulation, with some further enhancements following the 2014 Regulation. Historically $SF_6$ was simply vented to atmosphere during maintenance and at end-of-life. Now all gas is carefully recovered with specialised “recovery carts” (similar to RACHP refrigerant recovery machines) that compress and liquefy the $SF_6$ into a cylinder and clean out moisture and other contaminants. Ofgem licences incentivise reduced $SF_6$ leakage. For transmission voltages, the benchmark best practice leak rate is 0.5%. The emissions date reported by National Grid indicate there have been steady improvements in leakage (expressed as annual leakage as % of installed bank) during last 10 years.

In 2016 it was estimated that UK F-Gas emissions from GIS were 0.3 million tonnes $CO_2$ equivalent. This was around 2% of total UK F-Gas emissions in 2016. 2016 emissions were an estimated 13 tonnes of $SF_6$ from an equipment bank containing approximately 1,000 tonnes of $SF_6$. Hence the average leakage rate was 1.3%. It is estimated that 90% of the emissions are from the transmission networks and 10% from the distribution networks. The quantities of $SF_6$ emissions has fallen considerably during the last 10 years.

The current EU F-Gas Regulation has no controls over the use of $SF_6$ in new GIS. The existing controls reduce operational and end-of-life $SF_6$ losses. The bank of $SF_6$ in GIS has risen steadily during the last 10 years. However, bank growth is likely to stop and possibly reverse as older $SF_6$ equipment begins to require replacement and state-of-the-art $SF_6$ equipment is installed with much smaller $SF_6$ charge. Average leak rates can be expected to slowly improve as the old leaky $SF_6$ equipment is replaced with modern equipment which is more compact and has a lower level of leakage.

GIS equipment suppliers are investigating various alternatives to $SF_6$, recognising that the high GWP could be considered unacceptable in the long term. The two main options available are: 1) Alternative gases to replace $SF_6$ in GIS; 2) Alternative not-in-kind technologies to be used in place of GIS. The applicability of these different options depends on the size and voltage level of the current GIS application. National Grid are currently piloting new technology in the UK. During discussions with National Grid it has been noted that approximately half of the $SF_6$ used is in Gas Insulated Lines (GIL) rather than switchgear although this can be very installation dependant. Based on this, and the success of the $g^3$ GIL pilot (clarify), the potential for replacing a large proportion of $SF_6$ in new substation installations is already available, even if the new switch gear technology is not quite ready yet. National Grid have plans to replace two $SF_6$ sub-stations this year. The new ones will be $SF_6$ but with only 20% of the $SF_6$ charge and with much lower leak rates that equivalent technology of say 20 to 30 years ago. The replacement of large sub-stations like these is a slow and expensive process. There is at least a two year planning and building process, even after the design and technology of the sub-station has been agreed.

Because of the very long lifecycle of GIS equipment, the introduction of new low GWP gases will only have a small impact on emissions between now and 2032. In the short term, the most important action is minimisation of leakage from the existing bank, especially from the oldest and leakiest $SF_6$ equipment.

With current Regulations we estimate 2032 emissions of below 0.2 million tonnes $CO_{2eq}$. With the introduction of low $SF_6$ or $SF_6$-free systems from around 2025 and significant investment to replace the current stock, this could fall to below 0.1 million tonnes $CO_{2eq}$ by 2032. Because of the long lifecycle of $SF_6$ GIS, it will take until around 2065 to approach zero emissions.

The total costs of replacing all or part of the GIS and GIL equipment in the UK is difficult to quantify due to the size of the industry. However, most manufacturers as well as transmission and distribution operators are already “moving in the right direction”. Currently, non-$SF_6$ gases are more expensive than $SF_6$ – approximately four times more expensive. However, the price of gas is only a minimal factor in the overall cost of equipment. Non-$SF_6$ equipment is generally about 10-15% more expensive and additional space requirements where larger equipment is needed. Our modelling suggest that the marginal abatement costs will lie in the range 380 to 3,000 £ per tonne CO2e saved.

# 1 Introduction

## 1.1 The overall context

The work done under this contract has helped to generate the evidence base that the CCC needs for its analysis of optimal pathways to help the UK achieve its carbon budgets and the 2050 target under the Climate Change Act.

The Climate Change Committee's (CCC's) scenarios for meeting the fifth carbon budget set out a 68% cut in F-gas emissions from 2015 to 2030, involving reductions in emissions from refrigeration, air conditioning in buildings and vehicles and aerosols[1]. However, the evidence base in this area is old and as the CCC suspect, we can confirm it is now rather outdated. This has limited the CCC's ability to assess whether there is potential for the Government to implement policy that goes beyond the existing EU F-gas Regulation. This project answers the question about what opportunities there are to go beyond the EU regulatory minimums on F-gases, and, in which sectors the greatest opportunities lie with the greatest certainties of achieving reliable reductions.

**Box 1-1. Brief summary of the F-Gas regulations**

a) Phase-down of HFCs: a 79% cut in baseline consumption (average 2009 to 2012) by 2030
b) Reductions in use through 20 different F-Gas bans specified in Annex III of the 2014 Regulation and the ban in HFC use in car air-conditioning specified in the 2006 MAC Directive
c) Reductions in use created by various mandatory "management measures" including regular leak checks and repair, gas recovery at end-of-life, record keeping, training and certification of technicians and product labelling.

Note $SF_6$ and PFC are considered in the F-gas Regulations, but they are not included in phase-down controls. Some bans apply and management measures apply to applications such as $SF_6$ used in high voltage switchgear.

There are two important observations from recent CCC publications, both of which imply accelerated GHG mitigation action needs to be taken:

> **2017 Report to Parliament – Meeting Carbon Budgets: Closing the policy gap.** Published: 29 June 2017. "… *although good progress has been made to date, that progress is stalling. Since 2012, emissions reductions have been largely confined to the power sector, whilst emissions from transport and building stock are rising; effective new strategies and policies are urgently needed to ensure emissions continue to fall in line with the commitments agreed by Parliament*. "

> **UK Climate Action following the Paris Agreement (2016).** Published: 13 October 2016[2]. *"The report concludes that the Paris Agreement is a significant step forward in global efforts to tackle climate change. It is more ambitious in its aims to limit climate change than the basis of the UK's existing climate targets. However, it is not yet appropriate to set new UK targets. Existing targets are already stretching and the priority is to take action to meet them."*

This is the final report.

## 1.2 The broad analytical approach to the project

The project was split into 5 main tasks. An Expert Group was convened to provide expert input to the work, and, to help test the assumptions made in all Tasks, and in Task 3 in particular.

[1] See CCC (2017), Meeting Carbon Budgets: Closing the Policy Gap
[2] https://www.theccc.org.uk/publication/uk-action-following-paris/

**Table 1-1. Summary of the tasks within the project**

| Task | Outputs |
|---|---|
| **Task 1: Identification of potential F-gas alternatives** | • The main emission sources of F-gases, based upon UK greenhouse gas inventory data and the BEIS RAC model<br>• The main alternatives to each of the uses of F-gases |
| **Task 2: Assessment of future demand for F-gases and alternatives** | • Assumptions for future demand for the services that F-gases provide |
| | • Review of impact of the present F-gas Regulation and Kigali amendment on emissions reduction in the UK |
| **Task 3: Collection and analysis of cost and emissions data** | • Costs of existing and alternative technologies<br>• Direct emissions from these existing and alternative products<br>• How these costs (and other metrics) could develop over time and in particular where there is potential for cost reductions |
| **Task 4: Review of others barriers and opportunities** | • Qualitative assessment of any other costs and benefits that cannot be monetised<br>• Summarise non-financial barriers to uptake of the alternatives to each of the current F-gas applications and consider how these might be addressed |
| **Task 5: Determination of potential rates of uptake** | • Determination of potential rates of uptake |

The project considered both technical potential and cost effectiveness.

This report is not directly structured around the tasks, but rather, it presents a detailed assessment of the main sectors and sources where enhanced mitigation options, beyond the business as usual case, are real possibilities. For each source or source sector, it then presents the outputs from the analyses associated with the tasks.

It is important to bear in mind that there are considerable uncertainties associated with the future predicted F-gas emissions. Uncertainties associated with mitigation costs are probably greater still. Even taking these uncertainties into account, it is still possible to identify mitigation actions that are highly likely to be cost effective, and, to identify options which should clearly be rejected on grounds of technical feasibility and/or their costs.

# 2 Historical and projected F-gas emissions

## 2.1 F-gas reductions in the CCC's scenarios

The latest UK GHG projections have been generated by BEIS (2018) *Updated energy and emissions projections: 2017*[3]. The F-gas projections methodologies are summarised in "*Annex_n-Non_CO2_GHG_emissions_projections_report.pdf*". We have summarised the methodologies used in Table 2-1 below.

**Table 2-1. Current methodologies for projecting UK F-gas emissions used by BEIS as reported by the CCC**

| Sector | Approach |
|---|---|
| **Primary aluminium production** | We know the effect of all the recent abatement measures applied and we expect no further abatement so project constant emissions from aluminium production |
| **Magnesium cover gas** | We project magnesium emissions based on (i) sector expert knowledge on short term replacement of F-gases and (ii) long term replacement of F-gases due to the 2014 EU F-gas regulation |
| **Production of Halocarbons** | We project HFC emissions based on (i) short term company planning information and (ii) long term replacement of F-gases due to the 2014 EU F-gas regulation. We project PFC emissions to be constant, equal to the 10 year average as there is no discernible trend |
| **Metered Dose Inhalers** | Emissions are exempt from the 2014 EU F-gas regulation and we project emissions using population growth (**ONS**) as the driver |
| **Aerosols** | We project sector growth to be zero, in line with the trend in recent years, and model the gas bans and phase down resulting from the 2014 EU F-gas regulation |
| **Refrigeration & Air-conditioning** | We use the same model as used for the historical emissions calculation. Then assumptions are applied from the 2014 F-Gas regulation, most important of which is the HFC phase down which caps the amount of HFCs placed on the market each year. This model was reviewed and updated in 2015 by the Ricardo team of refrigeration and air-conditioning experts |
| **Foams** | We extend the mapping of activity and emissions to 2035 from the historical inventory model. This model was reviewed and updated in 2017 in line with the updated model produced for the 2016 GHGI submission. Then we model the gas bans and phase down resulting from the 2014 EU F-gas regulation. |
| **Firefighting** | We extrapolate the latest GHGI model out to 2050 using emissions factors based on UNFCCC sectoral guidance and Article 5 of the 2014 F-gas regulations |
| **Solvents** | We project sector growth to be zero, in line with the trend in recent years, and model the phase down resulting from the 2014 EU F-gas regulation |
| **High voltage switch-gear ($SF_6$)** | We project sector growth based on expert advice which is in line with **Schwarz et al (2011)**, assuming continuing decreasing leakage due to the 2006 and 2014 EU F-gas regulations |
| **Electronic manufacture** | Project constant emissions due to limitations in the historical data. |
| **AWACS ($SF_6$)** | Project constant emissions in line with historical data |
| **Training shoes (PFCs / $SF_6$)** | Emissions from this source have ceased and are not expected to resume, therefore we assume no emissions from this source in future years |
| **Particle accelerators ($SF_6$)** | Emissions are very small and are projected to be constant |
| **Tracer gas ($SF_6$)** | Project constant emissions based on last two years in the GHGI. |

The refrigeration and air conditioning sector (RAC) is currently the largest of the F-gas emitting sectors. With the addition of heat pumps (HP), the sector is referred to as the RACHP sector although currently the emissions form heat pumps are a very small component of the total emissions from the sector. Future government energy efficiency measures include heat pumps, so it was important to explicitly include this sector in our assessment.

[3] https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2017

Estimates of historical and projected emissions from the refrigeration and air conditioning sectors are derived from the BEIS F-gas emissions and projections model. Ricardo maintain this model for BEIS.

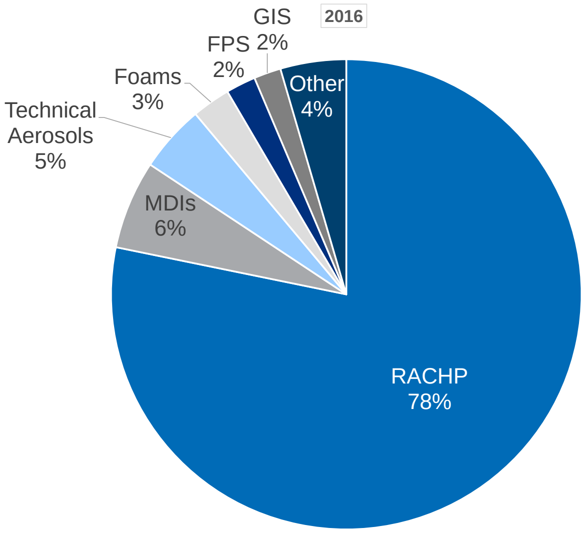
In 2015, Ricardo made a series of updates to the review the historical data in the model to identify issues caused either by incorrect calculation methodology or by incorrect input assumptions, and, considered the forecasting assumptions in each market sector, ensuring that they fully took into account the impact of the 2014 EU F-Gas Regulation. These are now included in the projections.

## 2.2 The current sectoral split in F-gas emissions

The current sectoral split is provided in the UK GHG inventory, submitted to the UNFCCC in 2018, containing the time series of emissions from 1990 to 2016. The “base year” for UK F-gas emissions is 1995. The Ricardo team create and report the UK’s GHG inventory. The inventory is reported to the UNFCCC, and under the EU Monitoring Mechanism Regulation with slightly modified geographical coverage to reflect the territories that are part of the EU. It is fully compliant with the UNFCCC reporting requirements, and reports emissions in the required IPCC categories.

Figure 2-1 shows the sectoral split in F-gas emissions in 2016. Total emissions are dominated by emissions from refrigeration, air conditioning, and heat pumps (RACHP). The GWP weighted F-gas emissions in 2016 are approximately 3% of net national emissions.

**Figure 2-1. Emissions of F-gases in 2016 (taken from the UK GHG inventory submission, 2018)**




## 2.3 Forecast of F-gas emissions based on current policies

Projections or forecasts of F-gas emissions are made periodically. The frequency of update depends on the sector and normally the projections are rebased as the historical emissions are updated. The methods used to forecast the F-gas emissions depend on the sector. In the case of the RAC sector, a stock model is used which simulates the quantities of F-gases in use, and this model makes predictions about how these quantities will change in the future. The drivers used to make these future estimates are sectorally specific. As an example, the future growth in population would be used to make projections of emissions from the use of MDIs.

Figure 2-2 shows the forecast of F-gas emissions based on current UK policies.

**Figure 2-2. Forecast of F-gas emissions based on current policies (k tonnes $CO_2$ eq.)**

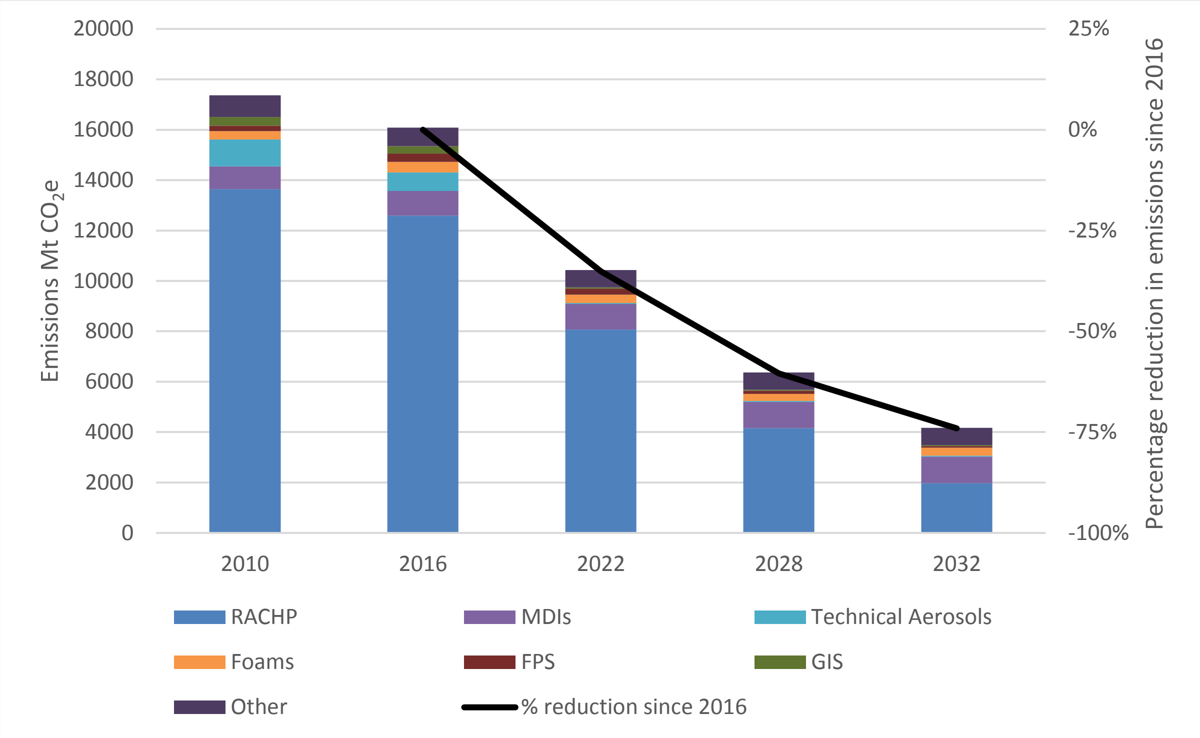
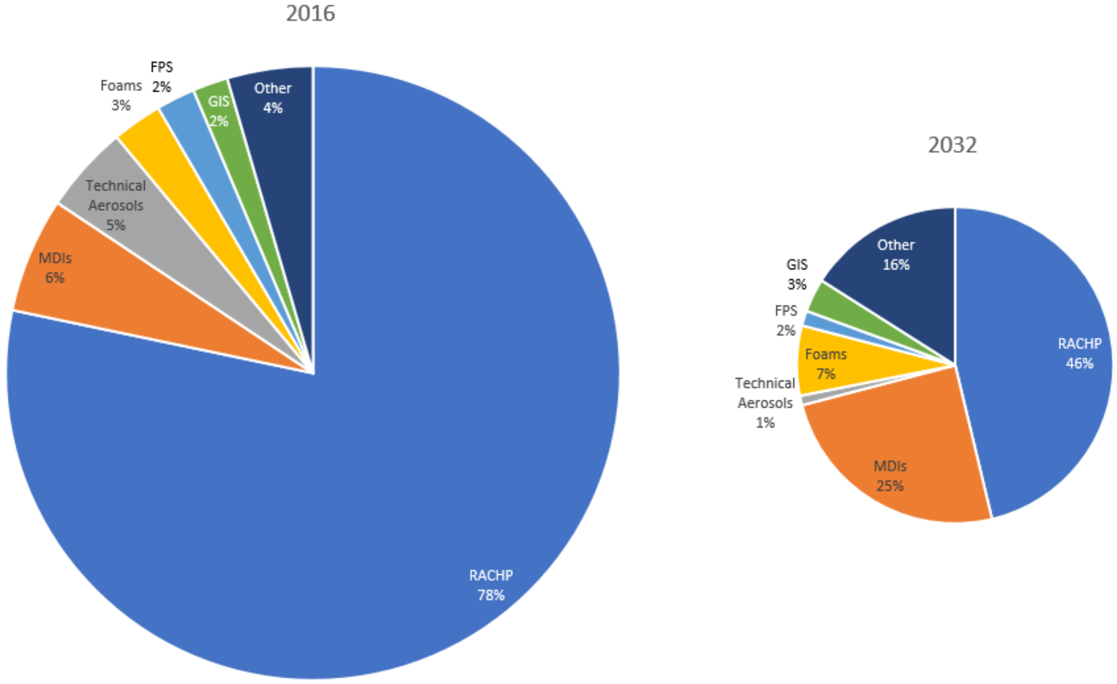



Figure 2-3 shows how the relative importance of each market sector changes between the latest year of the historical emissions, 2016, and 2032 which is the last year of the 5th carbon budget. The size of the pie charts is proportional to the magnitude of the total F-gas emissions, relative to 2016. RACHP dominates total F-gas emissions, on a GWP weighted basis, in both 2016 and 2032. But by 2032, MDIs and GIS have become a much greater fraction of the sector total emissions. The relative importance of foams has also grown, but where foams are used in building insulation, this is an application where recovery of the blowing agents used at the end of life is difficult because separation of the foam from the associated building material is technically extremely difficult.

**Figure 2-3. Change in relative importance of each market sector over time (GWP weighted basis)**




## 2.4 Which sectors have the greatest future potential for emission reductions?

To help provide context for this study, the team made scoping calculations to help the CCC judge the reductions that might be possible. Table 2-2 summarises our assessment of the sectoral reductions in emissions that might be possible by 2030, with some comments made on the reductions according to F-gas species also.

For each sector we estimated the impact of the 2014 F-Gas Regulation (plus the 2006 MAC Directive) by 2030. For some sectors this is a 100% reduction (e.g. foam blowing) because of bans in the Regulation. For some sectors there is little or no reduction (e.g. MDIs). We have then calculated a residual F-Gas use in 2030 and then provided a qualitative description of what else can be done. Finally, we have made an approximate estimate of further saving potential through “tougher Regulations”.

Not surprisingly, the F-Gas Regulation already creates big cuts in emissions – there is a 79% phase-down for HFCs, which are the dominant F-Gas in the UK inventory. Under the current EU F-Gas Regulation, the UK should cut emissions from 16.0 to around 3.5 Mt $CO_2$ eq. But, our analysis shows there is potential to cut the residual 3.5 Mt $CO_2$ eq. down further. We have highlighted the sectors that have the potential to deliver these cuts, and these were the focus of this study.

**Table 2-2. Scoping calculations to help the judge the sectoral reductions in emissions that might be possible by 2030**

| Sector | 2016 (estimated) UK Emissions | | Impact of F-Gas Regulation | Comments on F-Gas Regulation | Remaining MT $CO_{2\ eq.}$ in 2030 (Col G) | % of remaining 2030 use | Comments on further potential beyond F-Gas Regulation if CCC push for tougher Regulations |
|---|---|---|---|---|---|---|---|
| | MT $CO_{2\ eq.}$ | % of total | | | | | |
| **RACHP** | 12.6 | 78% | Significant | Combination of phase-down and bans | 3.0 | 57% | Good - over half of projected F-gas emissions for 2030 |
| **MDIs** | 1.0 | 6% | None | Excluded from any controls | 1.0 | 20% | Very good - DPIs can take significant market share. HFC-152a can replace HFC-134a. An over 90% cut is conceivable |
| **Technical Aerosols** | 0.7 | 5% | Significant | HFCs of GWP > 150 banned from 2018 | 0.0 | 1% | Little further potential |
| **Foam** | 0.4 | 3% | Significant | Bans in 2020 and 2023 | 0.3 | 6% | No further cost-effective potential, due to ongoing emissions being associated with leakage of gas from long lifetime foams that are challenging to effectively recover. |
| **FPS** | 0.3 | 2% | Moderate | Phase-down will raise prices | 0.1 | 2% | Good. Other FPS agents are available. Could impose stronger controls. |
| **Gas Insulated Switchgear** | 0.3 | 2% | Low | No $SF_6$ phase-down. Better leak management required | 0.1 | 2% | Leakage / recovery has room for improvement. New technology avoiding $SF_6$ might be available by 2030 |
| **Semiconductors** | 0.2 | 1% | Low | No PFC or $SF_6$ controls. HFCs excluded from phase-down | 0.2 | 4% | Difficult to improve. Worth re-checking UK estimates - might over-estimate current emissions due to drop in UK production. |
| **Halocarbons production** | 0.2 | 1% | Low | Very little impact on gas manufacture | 0.2 | 3% | Emissions from PFC manufacture seem very high - could be targeted by EA through IED |
| **Other** | 0.2 | 1% | Low | AWACs, Lab uses, etc. Very little control. | 0.1 | 3% | Difficult to improve. AWACs estimate worth checking (MOD have not released data) |
| **Solvents** | 0.1 | 0% | Low | Phase-down will raise prices | 0.1 | 1% | Worth re-checking UK estimates - might over-estimate current emissions. |
| **Magnesium** | 0.1 | 0% | Low | Controls on die-casting. UK uses other types of casting | 0.1 | 1% | Stricter controls on $SF_6$ use could be applied to sand casters and billet caster (Magnesium Elektron) |
| **Aluminium fugitives** | 0.0 | 0% | None | No controls | 0.0 | 0% | Difficult to improve |
| | **16.1** | | | | **5.3** | | |

Sectors with good potential to go further than current F-Gas Regulation

**Note:** This table reflects the status of the data availability and analysis at the start of the work.

In some sectors, further reductions in emissions are likely to be difficult or are technically difficult to achieve. These sectors are: technical aerosols, foams, semiconductors, AWACs, solvents, and fugitive emissions from aluminium production. During this project, effort was concentrated in the sectors which have the greatest likelihood of delivering reductions in F-gas emissions.

It was our judgement that the sectors that had the greatest potential for future further reductions in emissions were:

- Refrigeration Air Conditioning and Heat Pumps (RACHP)
- Metered Dose Inhalers (MDIs)
- Gas Insulated Switchgear (GIS).

The fire protection sector (FPS) was considered as a candidate sector for further investigation. The estimated possible further cut in emissions was similar in magnitude to that in the GIS sector. However, unlike GIS, the likely impact of the F-Gas Regulation on FPS was moderate, rather than low. Since the remit of this project was to look for enhanced mitigation options beyond those that were likely, and the resources allowed only a few sectors to be considered, this sector was not included in the more detailed analysis.

## 2.5 Convening the Expert Group

We created a “virtual Steering Group” that included experts on RACHP, MDIs and GIS. Two teleconferences were held to gather the views of the participants of the Expert Group, in particular to test our suggestions about the likely possible measures that could be taken to reduced emissions.

**Table 2-3. Composition of Expert Group**

| Expert | Group part | Specialist Sector |
|---|---|---|
| David Crawley | 1 | Gas Insulated Switchgear (GIS) |
| Ashley Woodcock | 1 | Metered Dose Inhalers (MDIs) |
| Davinder Lail | 2 | Defra Stratospheric Ozone and Fluorinated Gases Team |
| Graeme Maidment | 2 | Refrigeration and Air Conditioning (RAC) |

# 3 Enhanced mitigation options for Refrigeration, Air-conditioning and Heat Pumps (RACHP)

## 3.1 Background

Refrigeration, air-conditioning and heat pumps (RACHP) are the UK's main user and emitter of HFCs. Since the phase-out of ozone depleting refrigerants (CFCs and HCFCs), HFCs have become the main refrigerants used in a wide range of RACHP applications. For example:

- Supermarket / other food retail refrigeration uses mainly R-404A and other "400 series" blends[4]
- Building air-conditioning uses mainly R-410A[1] and R-134a
- Car air-conditioning uses R-134a
- Heat pumps use mainly R-410A and R-407C.

HFCs have been widely adopted as they are well suited to many RACHP applications. They have appropriate thermodynamic properties which are required to create efficient refrigeration cycles. Other key characteristics are that the popular HFCs are non-flammable and have very low toxicity. Prior to the introduction of controls on HFC use in the 2014 EU F-Gas Regulation[5], R-404A, R-410A and R-134a represented over 80% of refrigerants used in the UK.

A key drawback in the use of HFC refrigerants is that they are potent greenhouse gases (GHGs). The commonly used HFC refrigerants have global warming potential (GWPs) in the range 1400 to 4000. Table 3-1 illustrates GWPs of various refrigerants for comparison.

**Table 3-1: GWPs[6] of Various Refrigerants**

| Gas | GWP |
|---|---|
| R-404A | 3,922 |
| R-410A | 2,088 |
| R-407C | 1,774 |
| R-134a | 1,430 |
| HC-600a | 3 |
| R-717 | 0 |

Some parts of the RACHP market have been using non-HFC refrigerants for many years. In particular:

- Domestic refrigerators have been using a hydrocarbon (e.g. iso-butane, known as HC-600a) on a large scale in the UK since the early 2000s.
- Large industrial systems often use ammonia (R-717) – this refrigerant has been common throughout the last century. However, other refrigerants are also used; many industrial systems use HFCs such as R-134a and R-404A.

### 3.1.1 Impact of Current Regulations

It is important to note that the use of HFCs in RACHP systems is significantly affected by the 2014 EU F-Gas Regulation. Many of the requirements in that Regulation are leading to a change in refrigerant choices for new equipment and a change in operation and maintenance practices. Key aspects of the Regulation that affect RACHP include:

a) The HFC phase-down process, which will lead to a 79% cut in the GWP weighted quantity of HFCs that can be sold in the EU by 2030. Significant cuts are already in place – in 2018 the cut is 37% from the baseline.

b) Several bans that restrict the refrigerants that can be used in specific types of new RACHP equipment. Two bans are already in place (for HFCs in domestic refrigerators, since 2015 and for car air-conditioning, since 2017). Some further important bans start in 2020 and 2022 (affecting retail refrigeration systems, industrial refrigeration systems and very small air-conditioning equipment) and 2025 (affecting small air-conditioning equipment).

[4] Refrigerants in the "400-series" are blends of 2 or 3 different components. R-404A, R-410A and R-407C are all blends containing HFC components.

[5] EU Regulation 517/2014 on fluorinated greenhouse gases

[6] All GWPs in this report are 100-year values from the 4th Assessment Report of the IPCC. These are the values used in the 2014 EU F-Gas Regulation.

c) A ban on servicing of existing R-404A systems in medium and large sized supermarket and industrial systems, from 2020.

d) Various rules about leak prevention, mandatory leak testing, refrigerant recovery and technician training.

As discussed below in Section 3.3, the F-Gas Regulation is expected to reduce RACHP F-Gas emissions by 84% between 2016 and 2032. This is a significantly different characteristic to other sectors that are the focus of this study (MDIs and GIS). The use of HFCs for MDIs are not controlled by the F-Gas Regulation and the use of $SF_6$ in GIS is only constrained by rules on leak prevention, mandatory leak testing, refrigerant recovery and technician training. However, despite the significant F-Gas emission reductions that are expected from RACHP under the current Regulation, there may be further opportunities to reduce emissions to an even lower level and/or to bring down emissions more quickly.

### 3.1.2 Diversity of RACHP applications

It is important to recognise that the RACHP market is highly complex, with many different market sectors and sub-sectors. This leads to the need for a range of different refrigerants that are designed to suit specific applications. Key variables include:

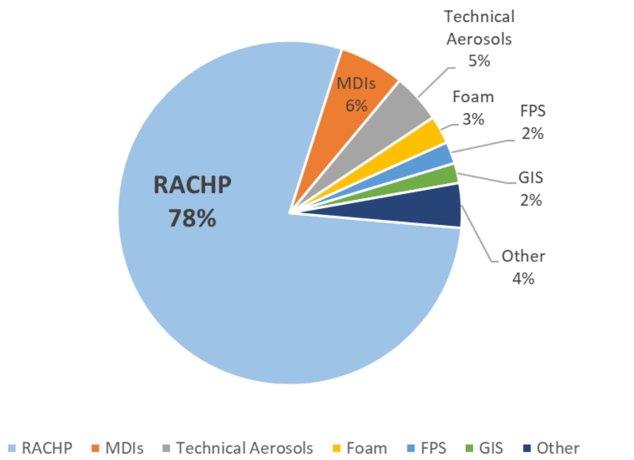
- **Size**: RACHP systems vary in cooling capacity from under 1 kW (e.g. domestic refrigerator) to >10,000 kW for large industrial systems.
- **Temperature level**: most refrigeration applications are either in the range 0ºC to 5ºC (e.g. for chilled food) or -15ºC to -40ºC (e.g. for frozen food). However, some refrigeration is required at much lower temperatures, between -60ºC and -270ºC. Air-conditioning typically provides cooling at temperatures in the range 10ºC to 20ºC. Heat pumps deliver heat at temperatures between 40ºC and 120ºC. This significant range of different temperatures requires various refrigerants to be available, with a range of thermodynamic properties that can be selected to suit the temperature level of the application.
- **Location / accessibility:** some RACHP systems are located in areas with public occupancy e.g. shops, hotels, private residences. In such locations safety issues might restrict the choice of available refrigerants or the size of refrigerant charge. For some RACHP applications, the equipment is located in a restricted area, with only trained personnel allowed access e.g. in factories or special machinery rooms. In these circumstances, a wider range of refrigerant options can be considered.
- **New equipment versus retrofits**: most refrigerant selections are made for new equipment, where the designer may have several options available. However, under an HFC phase-down it may also be appropriate to retrofit an existing plant with a lower GWP refrigerant. In these circumstances there are many more design constraints and fewer refrigerants will be suitable.

## 3.2 Current UK Use and Emissions

In the UK GHG Emissions Inventory emissions from RACHP are estimated using an RACHP emissions model, which is a “bottom-up stock model” of the various RACHP markets. This model also makes projections of future emissions. In each market an estimate is made of the number of pieces of equipment in use. Factors are applied for emissions during plant manufacture, normal operation and at end-of-life. The model predicts the consumption of HFCs in new equipment and to service existing equipment and emissions. The model uses 13 different market sectors to represent the many and varied parts of the RACHP market. The model is validated by comparing the bottom-up predictions of UK consumption of HFCs with top-down data collected from UK refrigerant suppliers.

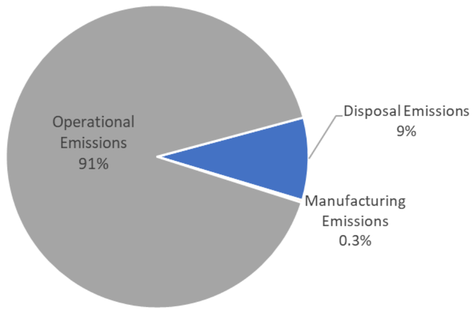
In 2016 it was estimated that UK F-Gas emissions from RACHP were 12.6 million tonnes $CO_2$ equivalent. This was 78% of total UK F-Gas emissions in 2016. Figure 3-1 illustrates the dominance of RACHP F-Gas emissions in 2016.

**Figure 3-1. Split of UK F-Gas Emissions 2016**



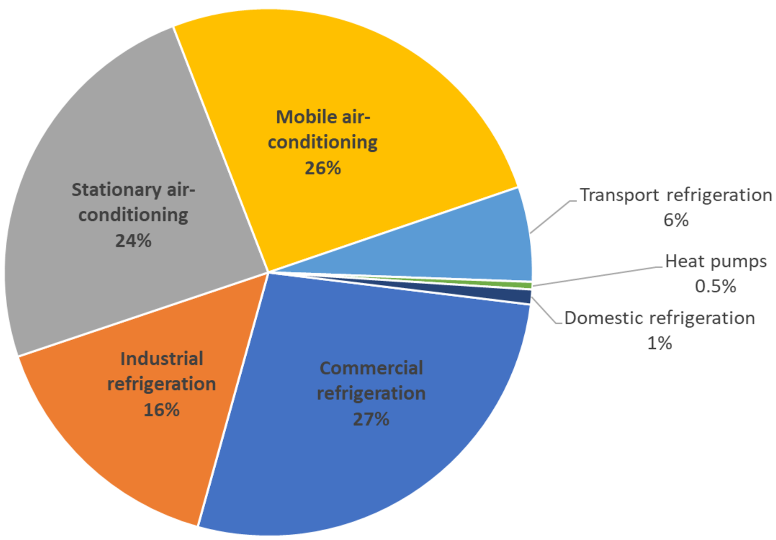

The modelling provides an estimated split between the RACHP emissions during operating life (i.e. leakage from existing equipment), emissions that occur when old systems are decommissioned at end-of-life and emissions that occur during the manufacture of new RACHP equipment. This is illustrated in Figure 3-2. Leakage emissions during operation are the dominant emission, with disposal emissions being significant. Emissions during equipment manufacture are negligible.

**Figure 3-2. Split of RAHCP F-gas Emissions 2016 (12.6 MT CO2)**




The split of 2016 emissions between RACHP market sectors is shown in Figure 3-3. Four sectors are dominant, representing over 90% of the total.

**Figure 3-3. Split of RAHCP F-gas Emissions 2016 (12.6 MT CO2)**



## 3.3 Emissions Projections, 5th Carbon Budget Period

As described in Section 3.1, the current EU F-Gas Regulation is expected to have a significant impact on the RACHP sector. The RACHP emissions model provides projections of emissions to 2040. The assumptions made in the forecasts include:

a) Compliance with all ban dates for new equipment. This forces a shift towards lower GWP refrigerants in markets that are targeted by bans.

b) More widespread adoption of lower GWP refrigerants in new equipment, driven by expert judgment of the impact of the price pressure created by the HFC phase-down process.

c) Compliance with the service ban on larger retail and industrial refrigeration equipment.

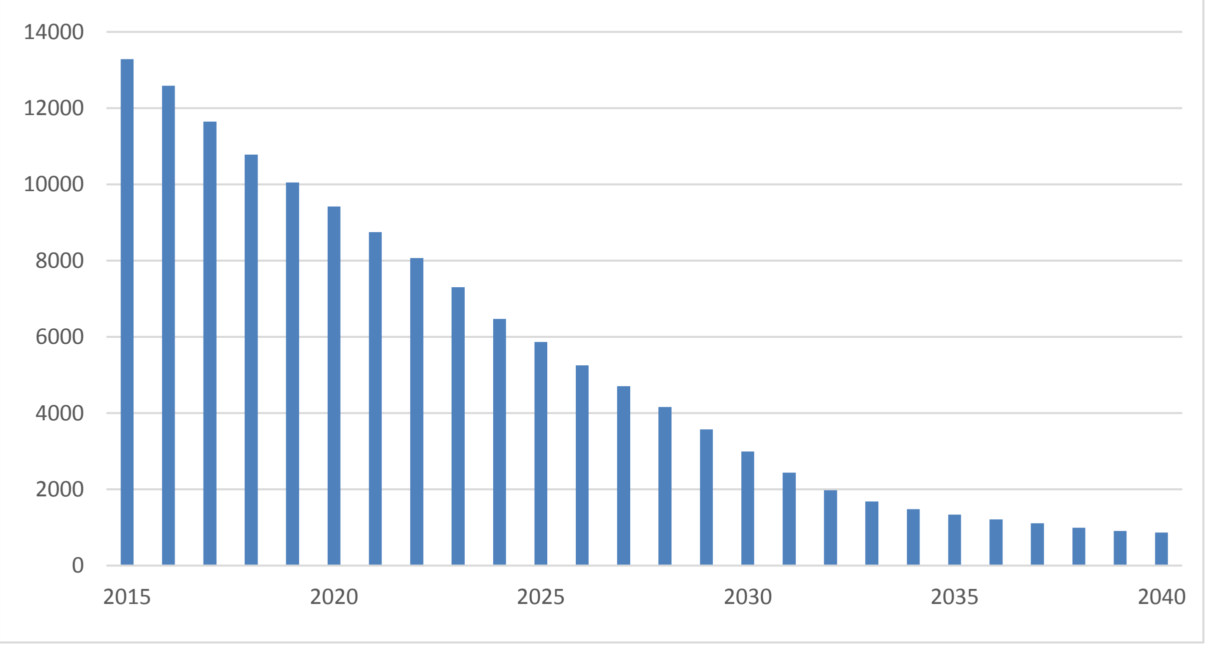
d) Improvements in leakage rates driven by rules on refrigerant handling and the price pressure created by the HFC phase-down.

The modelling allows for market growth in some RACHP sectors – especially the heat pump sector which is expected to grow to support Government efforts to reduce $CO_2$ emissions from the building space heating sector.

Figure 3-4 illustrates the expected total RACHP emissions to 2040. Emissions fall from 12.6 million tonnes $CO_2$ equivalent in 2016 to:

- 4.2 MT $CO_2$ in 2028 (a 67% cut from 2016)
- 2.0 MT $CO_2$ in 2032 (a 84% cut from 2016)
- 0.9 MT $CO_2$ in 2040 (a 93% cut from 2016)

**Figure 3-4. Total UK RACHP F-gas Emissions 2010 to 2040, Current policies**



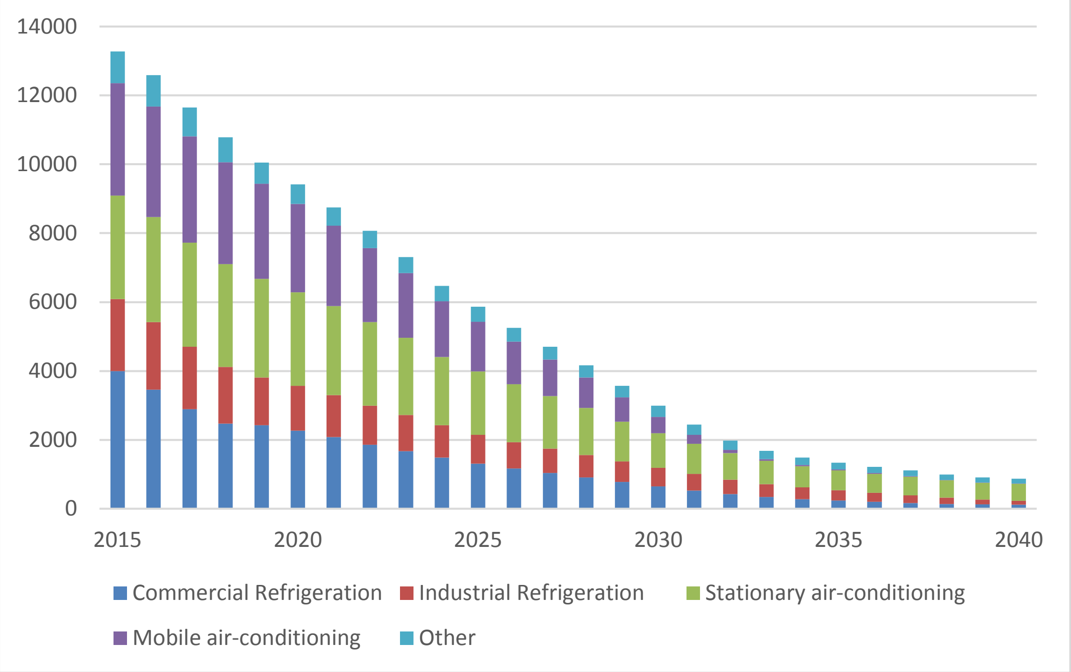

The rate of emission reduction takes into account the lifecycle of equipment in different parts of the RACHP market. For example:

a) In the car air-conditioning sector, there was a ban on the use of R-134a for all new cars from January 2017. The lifecycle of a typical car is around 10 years. By the start of the 5th Carbon Budget Period in 2028 one would expect almost 100% of the car fleet will have switched to a new low GWP alternative refrigerant to R-134a.

b) In the industrial refrigeration sector, equipment has a lifecycle of over 30 years. Hence around half of the industrial refrigeration equipment in current use will still be operating in 2032. By 2040 only a small proportion will still be in use.

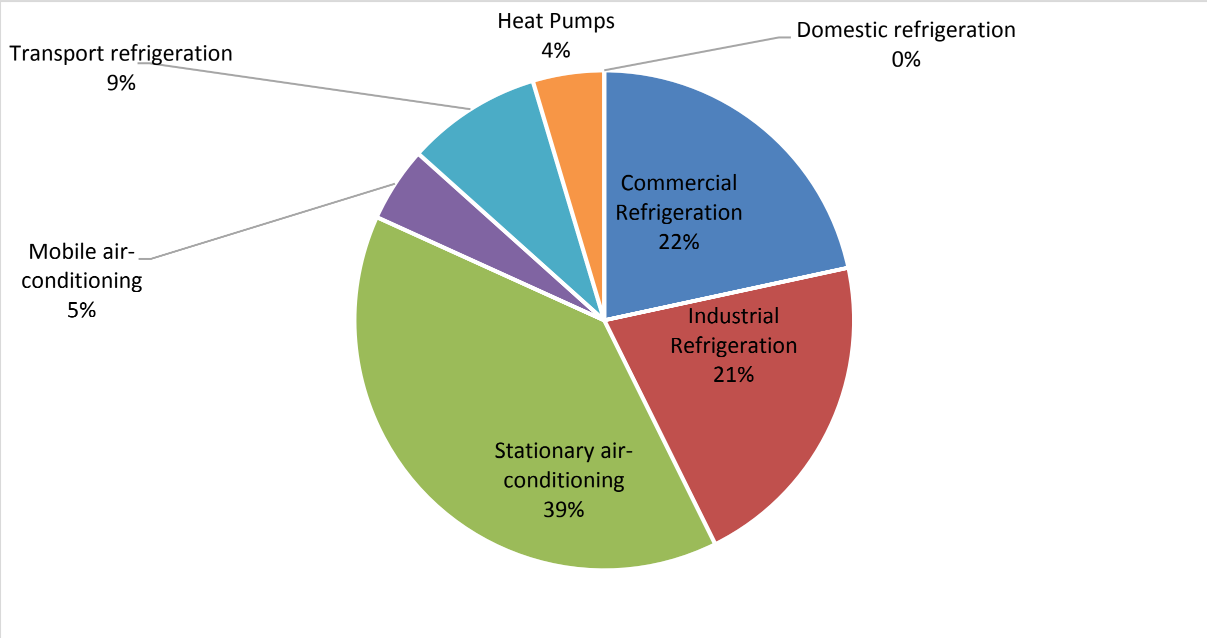
Figure 3-5 illustrates the emissions trends for the four largest sectors of the RACHP market. By 2032 emissions from the two largest emitters in 2016 (commercial refrigeration and mobile air-conditioning) are expected to have fallen to a very low level, whereas emissions from industrial refrigeration and building air-conditioning have not fallen as much. This is partly the lifecycle impact described above and also because in parts of the building air-conditioning market there are fewer low GWP alternatives available.

**Figure 3-5. F-gas emission trends for four largest RACHP sectors in 2016 and residual, 2015 to 2040**




The split between different sectors of the RACHP market in 2032 is illustrated in Figure 3-6. This split can be compared to the 2016 split in Figure 3-3 – but note that the 2032 pie represents only 2.0 MT $CO_2$eq, compared to 12.6 MT $CO_2$eq in 2016).

**Figure 3-6. Split of RACHP F-gas emissions 2032 (2.0 MT $CO_2$eq)**




An interesting difference between 2016 and 2032 is the split of emissions between operational leakage and end-of-life disposal. Figure 3-7 can be compared with Figure 3-3. The end-of-life emissions grow from 9% to 23% of the total. The total bank of installed equipment containing HFCs has reduced considerably by 2032, hence operational leakage falls quickly, whilst older equipment is being retired at an approximately constant rate through the 2020s as illustrated in Figure 3-8. This emphasises the possible importance of improving end-of-life recovery rates.

**Figure 3-7. Split of RACHP F-gas emissions 2032 (2.0 MT $CO_2$ eq)**

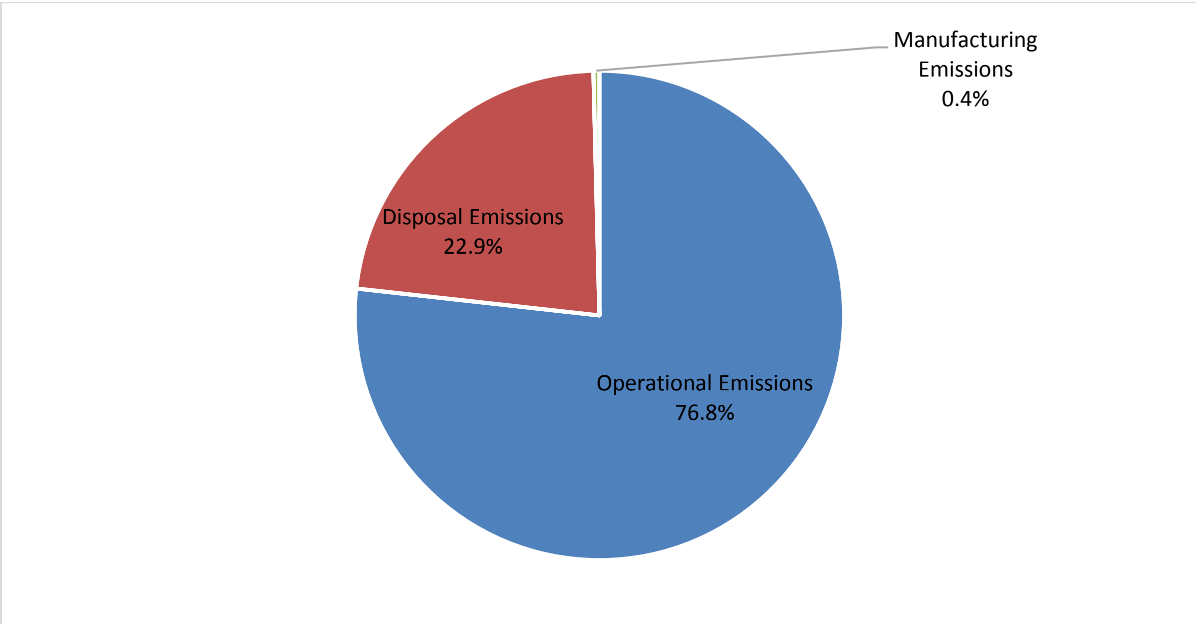
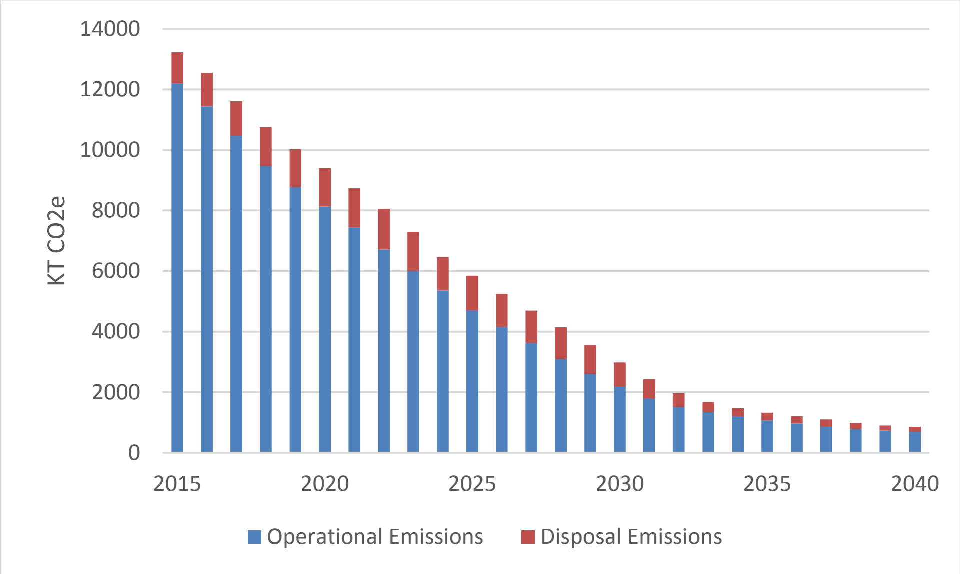


**Figure 3-8. Trend of operational and disposal F-gas emissions, 2015 to 2040**




# 3.4 RACHP F-gas alternatives and improvements

## 3.4.1 Low GWP alternatives

There are 3 different ways in which the RACHP industry is trying to address the tough requirements set by the EU HFC phase-down:

- **To use low GWP alternative refrigerants in new equipment**. In the long-term this is the most important option – by 2050 it could lead to almost the total elimination of the current generation of high GWP HFCs. However, because of the long lifecycle of some RACHP equipment, it will take many years before the existing bank of HFCs is totally replaced.
- **To reduce the usage of HFCs in existing equipment**. A significant proportion of total HFC consumption is to top-up leaks from existing RACHP equipment. By making investments in leak prevention this quantity can be reduced. For certain refrigerants it is also possible to consider retrofitting existing equipment with a lower GWP alternative refrigerant.
- **To make use of reclaimed refrigerant**. Old equipment reaching end-of-life contains HFCs. It is illegal to vent these HFCs to atmosphere – the F-Gas Regulation has a mandatory requirement for the old HFC to be recovered. This "second-hand" refrigerant can be reprocessed and re-used outside of the phase-down quota mechanism. This does not directly reduce F-Gas emissions but it does encourage maximum gas recovery and it can help the industry meet the very challenging HFC phase-down targets.

### 3.4.1.1 Alternative low GWP Gases

Numerous low GWP refrigerants are being considered as alternatives for the popular high GWP HFCs. A fairly small number of HFC refrigerants were able to satisfy the varied needs of the major RACHP applications. In the "HFC-era" just 4 HFCs dominated the total consumption of HFC refrigerants: R-404A, R-410A, R-407C and R-134a (see Table 1 for the GWPs of these refrigerants).

Table 3-2 lists 26 lower GWP refrigerants that are currently either in use or recently commercialised. The list is not fully comprehensive and there are likely to be other lower GWP options added to this list in the near future. The RACHP market does not need such a wide choice of options – the long list reflects the "immature" nature of the market and the uncertainties over which refrigerants will become dominant in the future.

The reason why so many different gases are under consideration is because:

a) The RACHP market is so complex with many diverse requirements, as described in Section 3.1. Refrigerants with different thermodynamic properties are required for different temperature levels and different system size.

b) The acceptability of flammable refrigerants is highly dependent on the characteristics of the application in terms of system size and location.

Ideally, we would use refrigerants from the lowest GWP categories in Table 3-2. Whilst there are 8 refrigerants listed with a GWP below 10, these are not suited to every application.

**Table 3-2: Lower GWP Alternatives**

| Refrigerant | | GWP | ODP[7] | Safety class[8] | NBP[9] (ºC) | Alternative to: | Markets, Applications and Other Comments |
|---|---|---|---|---|---|---|---|
| GWP <10 | R-717 (ammonia) | 0 | 0 | B2L | -33.3 | R-22, R-404A, R-134a | Mainly used in industrial refrigeration applications. Has been used in such applications for many decades, hence good technical experience is widely available. Also suited to large water chillers. Toxicity and materials compatibility issues typically limit applicability to large systems in restricted access areas. |
| | R-744 ($CO_2$) | 1 | 0 | A1 | -78.4 | R-22, R-404A, R-134a | Was used prior to 1950s, but replaced by CFCs. Re-introduced around 2005 and becoming widely used in supermarket refrigeration and some other applications. A1 safety classification is helpful, but operating pressures are very high and critical temperature is very low – this requires significant design changes. |
| | R-290 (propane) | 3 | 0 | A3 | -42.1 | R-22, R-410A | Used in small sealed refrigeration and heat pump systems and in medium and large sized water chillers. Being considered for small split air-conditioning. |
| | R-600a (iso-butane) | 3 | 0 | A3 | -11.8 | R-134a | Widely used in domestic refrigerators and other very small sealed systems. |
| | HFO-1234yf | 4 | 0 | A2L | -29.4 | R-134a | Becoming widely used as an alternative to R-134a in car air-conditioning. Being considered for other R-134a applications. |
| | HFO-1234ze | 7 | 0 | A2L | -19.0 | R-134a | Becoming widely used as an alternative to R-134a in medium pressure water chillers for air-conditioning and industrial process cooling. |
| | HFO-1233zd | 4 | 0 | A1 | 18.1 | R-123 | These refrigerants are being used in low pressure chillers as an alternative to R-123 (an HCFC). R-514A is a blend of HFO-1336mzz and R-1130 (trans-1,2-dichloroethene) and has properties that are very close to R-123. Both are non-flammable and capable of very high energy efficiency in low pressure chillers. |
| | R-514A | 7 | 0 | B1 | 29.1 | R-123 | |

[7] Ozone Depleting Potential
[8] SO 817: 2014 Refrigerants -- Designation and safety classification. The first letter indicates the toxicity (A being low) and the rest indicates the flammability, 1 being low, and 2L being between 1 and 2.
[9] Normal Boiling Point

| Refrigerant | | GWP | ODP[7] | Safety class[8] | NBP[9] (ºC) | Alternative to: | Markets, Applications and Other Comments |
|---|---|---|---|---|---|---|---|
| GWP 10-150 | R-454C | 148 | 0 | A2L | -46.0 / -37.8 | R-404A | These are HFC / HFO blends with characteristics similar to R-404A, being considered for use in various lower temperature refrigeration applications e.g. frozen food processing and storage. |
| | R-455A | 148 | 0 | A2L | -56.1 / -39.1 | R-404A | |
| | R-459B | 144 | 0 | A2L | | R-404A | |
| GWP 150-700 | R-32 | 675 | 0 | A2L | -51.7 | R-410A | R-32 becoming widely used in small split air-conditioning systems and small chillers as an alternative to R-410A |
| | R-447B | 741 | 0 | A2L | -50.0 / -46.0 | R-410A | These blends all contain a significant proportion of R-32 (65% to 70%) plus other components including HFOs. All are possible alternatives to R-410A |
| | R-452B | 675 | 0 | A2L | -51.0 / -50.3 | R-410A | |
| | R-454B | 466 | 0 | A2L | -50.9 / -50.0 | R-410A | |
| | R-459A | 459 | 0 | A2L | | R-410A | |
| | R450A | 605 | 0 | A1 | -23.4 / -22.8 | R-134a | These are non-flammable HFC / HFO blends with characteristics similar to R-134a |
| | R513A | 631 | 0 | A1 | -29.2 | R-134a | |
| | R-454A | 239 | 0 | A2L | -48.4 / -41.6 | R-404A | HFC / HFO blend with characteristics similar to R-404A |
| GWP 700-1400 | R-448A | 1387 | 0 | A1 | -45.9 / -39.8 | R-404A | These are non-flammable HFC / HFO blends with characteristics similar to R-404A. First introduced around 2015 and already gaining a significant market share in countries with HFC phase-down controls. |
| | R-449A | 1397 | 0 | A1 | -46.0 / -39.9 | R-404A | |
| | R-449C | 1251 | 0 | A1 | -44.6 / -38.1 | R-407C, R-22 | Non-flammable HFO / HFC blend being considered for bus and train air-conditioning |
| GWP 1400-2500 | R-452A | 2140 | 0 | A1 | -47.0 / -43.2 | R-404A | These are non-flammable HFC blends with characteristics similar to R-404A. R-407A and R-407F have been available since around 2010 or earlier and have been used in some commercial refrigeration applications. |
| | R-407A | 2107 | 0 | A1 | -45.3 / -38.9 | R-404A | |
| | R-407F | 1825 | 0 | A1 | -46.1 / -39.7 | R-404A | |

#### 3.4.1.2 Progress towards using low GWP gases

The relative size of the various RACHP markets are summarised in Table 3-3. This shows the "GWP-weighted" use of HFC refrigerants in 2012 – this year represents a time when the HFC market was mature in the UK and the impact of HFC phase-down policies had not yet begun.

Table 3-3 shows that a small number of market sectors dominate the total demand for HFCs. Four of the 14 market sub-sectors listed in Table 3-3 represent around 70% of total GWP-weighted HFC consumption (small air-conditioning, mobile air-conditioning, centralised retail refrigeration and water chillers). Progress towards lower GWP alternatives is good or very good in these large sectors.

Clear trends towards lower GWP refrigerants are beginning to emerge in some RACHP markets. In the markets labelled "Very good" in Table 3-3 there are already strong shifts towards ultra-low GWP options in the UK. In markets labelled "Good" there are shifts towards moderate GWP alternatives. In other markets, the picture is not yet so certain and progress towards lower GWP refrigerants is fairly slow. The sectors with slow progress mostly consist of users of medium sized systems that are located in public access areas. They are too large to safely use flammable refrigerants, but not large enough to be located in restricted access areas.

The lower GWP refrigerant trends for the 14 market sub-sectors listed in Table 3-3 are summarised in more detail in Table 3-4.

**Table 3-3: Estimate of RACHP Market Size and Progress**

| | Main sector | Sub-sector | Typical refrigerant charge (kg) | % of GWP-weighted HFC consumption in RACHP in 2016 | Progress to lower GWP |
|---|---|---|---|---|---|
| Refrigeration | Commercial (Retail) | Small sealed | 0.1 to 1 | 1% | Very good |
| | | Condensing units | 1 to 10 | 8% | Slow |
| | | Multi-compressor racks | 20 to 200 | 14% | Very good |
| | Industrial | Large | 100 to 2000 | 11% | Very good |
| | | Medium / small | 10 to 100 | | Poor |
| | Transport | | 2 to 10 | 5% | Reasonable |
| | Domestic | | 0.05 to 0.2 | 0% | Very good |
| | **Sub-total for refrigeration** | | | **49%** | |
| Air-conditioning / HP | Air to air | Small | 0.5 to 3 | 15% | Good |
| | | Medium | 3 to 12 | 1% | Reasonable |
| | | Large VRF | 12 to 100 | 7% | Slow |
| | | Large ducted | 12 to 100 | | Slow |
| | Water chillers | | 20 to 500 | 6% | Very good |
| | Mobile | Cars and vans | 0.4 to 0.8 | 17% | Very good |
| | | Buses, trains etc. | 1 to 10 | 4% | Slow |
| | **Sub-total for air-conditioning and heat pumps** | | | **51%** | |

**Table 3-4: Refrigerant Trends**

| Main Market | Market Sub-sector | Typical refrigerant charge (kg) | Most widely used HFCs | Progress to lower GWP | Comments |
|---|---|---|---|---|---|
| **Commercial Refrigeration**<br><br>including supermarkets, smaller food retail and food service (restaurants, hotels etc.) | Small sealed units | 0.1 to 1 | R-404A<br>R-134a | **Very Good**<br>Several ultra-low GWP options already available | There is significant use of hydrocarbons (R-290 or R-600a), especially for systems containing <0.15 kg. Some safety standards already allow higher charges and others are under review and may allow higher HC charges (e.g. 0.5 to 1 kg).<br>This market sub-sector is also well suited to ultra-low GWP 2L refrigerants (such as R-1234yf or R-1234ze) or low GWP R-404A alternatives (such as R-454C or R-455A). |
| | Condensing units | 2 to 10 | R-404A<br>R-134a | **Poor**<br>Progress is slow for the medium sized equipment in this market sector. | R-404A (GWP 3922) can be avoided quickly through use of medium GWP non-flammable alternatives such as R-448A and R-449A (GWP ~1400) or R-452A (GWP 2140).<br>The charge should be low enough for successful use of 2L low GWP R-404A alternatives such as R-454C or R-455A (GWP ~150), but more development is required. For chill temperatures (0 to +5 ºC) ultra-low HFO-1234yf or HFO-1234ze are possible 2L options.<br>$CO_2$ systems are currently too expensive in this size range, but prices are beginning to fall and $CO_2$ could become an option, especially in cool / mild climates. Small sized $CO_2$ condensing units may lack the efficiency required in hot climates. |
| | Large multi-compressor rack systems | 20 to 200 | R-404A<br>R-134a | **Very Good**<br>There is significant progress towards the use of ultra-low GWP options. | Transcritical $CO_2$ systems are being rapidly adopted in locations with cool / mild climates. In very hot climates cascade type $CO_2$ systems may be a better option.<br>Some supermarket companies are replacing large central systems with small sealed units cooled by a chilled water loop. The sealed systems are small enough to safely use higher flammability HCs such as R-290. New systems using R-448A and R-449A are becoming common.<br>Retrofit of large R-404A systems with non-flammable alternatives such as R-448A and R-449A is an important option. This can provide quick reductions in HFC consumption and has been shown to also provide very useful energy efficiency improvements. |

**Table 3-4: Refrigerant Trends**

| Main Market | Market Sub-sector | Typical refrigerant charge (kg) | Most widely used HFCs | Progress to lower GWP | Comments |
|---|---|---|---|---|---|
| **Transport refrigeration** | Refrigerated trucks, vans and iso-containers | 2 to 10 | R-404A<br>R-134a | **Reasonable**<br>There is some progress but more work is required | R-452A (GWP 2140) is a preferred option as its compressor discharge temperature is similar to R-404A. This provides flexibility for use in a wide range of ambient conditions.<br>$CO_2$ (R-744) is being trialled and initial results look encouraging, but this is not yet a widely available option. It is not yet clear if 2L refrigerants will be acceptable due to strict flammability rules that apply in some transport regulations. |
| **Industrial refrigeration** | Large | 100 to 2000 | R-404A<br>R-507A<br>R-407C<br>R-134a | **Very Good**<br>Several ultra-low GWP options already widely available | Ammonia (R-717) has been used in the industrial sector throughout the last 100 years. It is well suited to large industrial systems such as cold storage warehouses, blast freezers, large glycol chillers, providing cost effective equipment and potential for high energy efficiency. Large factories have restricted access, so the toxic and lower flammability characteristics of ammonia can be safely dealt with on large industrial plant.<br>Recently $CO_2$ (R-744) has been re-introduced and it can provide a good alternative to ammonia, especially in cascade systems.<br>Some large industrial applications are cooled with glycol or chilled water secondary refrigerants. A range of ultra-low GWP options are available, including ammonia, propane (R-290) and various HFOs (see section below on water chillers for air-conditioning – such chillers can also be appropriate for industrial plants). |
| | Medium / small | 10 to 100 | | **Poor**<br>Progress is slow for small / medium sized equipment | A significant proportion of industrial plant is small or medium sized. This makes it more difficult to use ammonia cost effectively. R-404A (GWP 3922) can be avoided quickly through use of medium GWP non-flammable alternatives such as R-448A and R-449A (GWP ~1400).<br>In the industrial market it should be possible to make use of 2L low GWP R-404A alternatives such as R-454C or R-455A (GWP ~150), but more development is required. For chill temperatures (0 to +5 ºC) ultra-low HFO-1234yf or HFO-1234ze are possible 2L options.<br>Some industrial processes require very low temperatures (e.g. below -60ºC). None of the "mainstream" refrigerants are suitable for such low temperatures and the currently available options have very high GWP. Because these are very small markets there is little development of lower GWP refrigerants for such applications. |

**Table 3-4: Refrigerant Trends**

| Main Market | Market Sub-sector | Typical refrigerant charge (kg) | Most widely used HFCs | Progress to lower GWP | Comments |
|---|---|---|---|---|---|
| **Domestic refrigeration** | Refrigerators and freezers | 0.05 to 0.2 | R-134a | **Very Good**<br>Ultra-low GWP options already widely available | There is widespread use of iso-butane (R-600a) in many geographic regions. Some safety standards allow use of up to 0.15 kg of this higher flammability refrigerant which is sufficient for most sizes of refrigerator and freezer. Hundreds of millions of iso-butane refrigerators are already in use globally. Some countries have had standards or legislation that restricts HC use (e.g. in the USA, where charge was limited to only 0.05 kg) but these are under review and it is likely that iso-butane will be used in the majority of countries in the future.<br>Refrigerators are also suited to ultra-low GWP 2L refrigerants (such as R-1234yf or R-1234-ze), although little product development has yet taken place. |
| Air to air air-conditioning | Small split systems | 0.5 to 3 | R-410A | **Good**<br>Rapid progress to moderate GWP options in a growing part of market | R-32, a moderate GWP 2L lower flammability refrigerant is rapidly gaining a significant market share in some geographic regions (e.g. it has completely replaced R-410A in Japan). It provides good energy efficiency and around a 75% reduction in GWP-weighted refrigerant charge. Safety standards allow use of 2L refrigerants in this size range in most locations. Other similar moderate GWP alternatives such as R452B and R-454B can also be considered.<br>At the small end of this size range, ultra-low GWP propane (R-290) is being used by some manufacturers although there is significant market resistance due to the higher flammability. |
| | Medium sized split systems | 3 to 12 | R-410A | **Reasonable**<br>Progress is slower than small splits | Most medium sized splits are still using R-410A. There is some progress towards the adoption of R-32 and similar 2L refrigerants.<br>Propane cannot be safely used in this size of split system. |

**Table 3-4: Refrigerant Trends**

| Main Market | Market Sub-sector | Typical refrigerant charge (kg) | Most widely used HFCs | Progress to lower GWP | Comments |
|---|---|---|---|---|---|
| | Large VRF systems | 12 to 100 | R-410A | **Slow**<br>Large charge size makes use of flammable refrigerants difficult | As charge sizes rise it becomes difficult to find a suitable alternative due to concerns about flammability. The latest safety standards allow charges of over 50 kg if the equipment incorporates “risk mitigation” features e.g. leak detectors by each indoor unit combined with automatic shut-off valves and automatic forced ventilation. However, there is currently little experience in this area and it is likely to be a few years before 2L refrigerants are widely used for VRF air-conditioning equipment. |
| | Large ducted systems | 12 to 100 | R-134a | | As for VRF systems, flammability is a barrier with such large charges. There are medium GWP non-flammable alternatives available for R-134a i.e. R-450A and R-513A. These both have a GWP around 600, which is less than half the GWP of R-134a. |
| Water chillers for air-conditioning | Low pressure chillers | 250 to 500 | None suitable | **Very Good**<br>Several ultra-low GWP options already available | Most large low pressure centrifugal chillers currently use an HCFC, R-123. They are not usually manufactured using HFCs.<br>Some of the new HFO refrigerants are well suited to large low pressure centrifugal chillers. These ultra-low GWP options include R-1233zd and R-514. These are both non-flammable. It is likely that there will be renewed interest in low pressure chillers as they are highly energy efficient and there are good ultra-low GWP options. |

**Table 3-4: Refrigerant Trends**

| Main Market | Market Sub-sector | Typical refrigerant charge (kg) | Most widely used HFCs | Progress to lower GWP | Comments |
|---|---|---|---|---|---|
| | Medium pressure chillers | 50 to 250 | R-134a | | Medium pressure chillers use either small centrifugal compressors or screw compressors.<br>The ultra-low GWP HFO-1234ze is becoming widely available for medium pressure chillers. HFO-1234yf is also used. They are 2L lower flammability – this does not usually create any safety barriers as chillers are mostly located in restricted areas. R-513A is also being adopted by several major chiller manufacturers where non-flammability is an important requirement.<br>Ammonia and HCs can also be used for screw compressor medium pressure chillers although it seems likely that HFO-1234ze will provide a lower cost option. |
| | High pressure chillers | 20 to 50 | R-410A | **Good**<br>Moderate GWP options being introduced | High pressure chillers are usually used for small chillers, using scroll or reciprocating compressors. R-32 and blends such as R-452B and R-454B are moderate GWP lower flammability alternatives to R-410A in these applications.<br>Propane (R-290) is an ultra-low GWP higher flammability option. |
| Mobile air-conditioning | Cars and vans | 0.4 to 0.8 | R-134a | **Very Good**<br>Switch to ultra-low GWP option | This market sector can switch to ultra-low alternatives quickly. Significant use of R-1234yf already taking place, driven by a ban on R-134a in new cars in the EU. Multi-national car manufacturers are expected to switch to this refrigerant globally over the next few years. |
| | Buses and trains | 1 to 10 | R-407C and R-410A | **Slow**<br>More work required | Progress is slow for the medium sized equipment in this market sector. The non-flammable medium GWP refrigerant R-449C is being considered for these applications. Various 2L lower flammability refrigerants may be suitable e.g. R-32, R-452B or R-454B, but it is not yet clear if any level of flammability is acceptable in these transport applications. |

### 3.4.2 Possibilities for reducing emissions from RACHP

As discussed in section 3.3, current Regulations should provide significant cuts from the RACHP sector by the 5th Carbon Budget period and even greater cuts by 2040.

It is important to note that by the late 2030s the HFC emissions from RACHP begin to stabilise at just below 1.0 MT $CO_{2eq}$ per year. This represents the residual use of HFCs in applications for which the current modelling has forecast no lower GWP alternatives. However, it should be noted that the forecasts were originally made in 2011 and were last updated in 2015.

Given the high percentage cuts that are expected under current Regulations, it should be recognised that there are three possible strategies that would lead to even lower emissions:

a) To cut the residual HFC quantity to a lower level.

b) To accelerate the switch to lower GWP refrigerants, especially in the period 2020 to 2030.

c) To further reduce leakage rates from RACHP equipment.

#### 3.4.2.1 Reducing residual emissions in 2040

Figure 3-3 and Figure 3-6 illustrate the forecast split of RACHP emissions in 2016 and in 2032. This showed how the emissions split shifted away from car air-conditioning and commercial refrigeration (in 2016) towards a greater proportion of Reducing residual emissions in 2040stationary air-conditioning. Figure 3-9 shows the split in 2040. This illustrates a continuing shift to a greater proportion of HFC emissions from stationary air-conditioning applications and from heat pumps. The shift between market sectors is shown in Figure 3-10, which shows the trend in the % split between the seven main RACHP market sectors.

**Figure 3-9. Split of RACHP emissions 2040 (0.9 MT $CO_{2eq}$)**

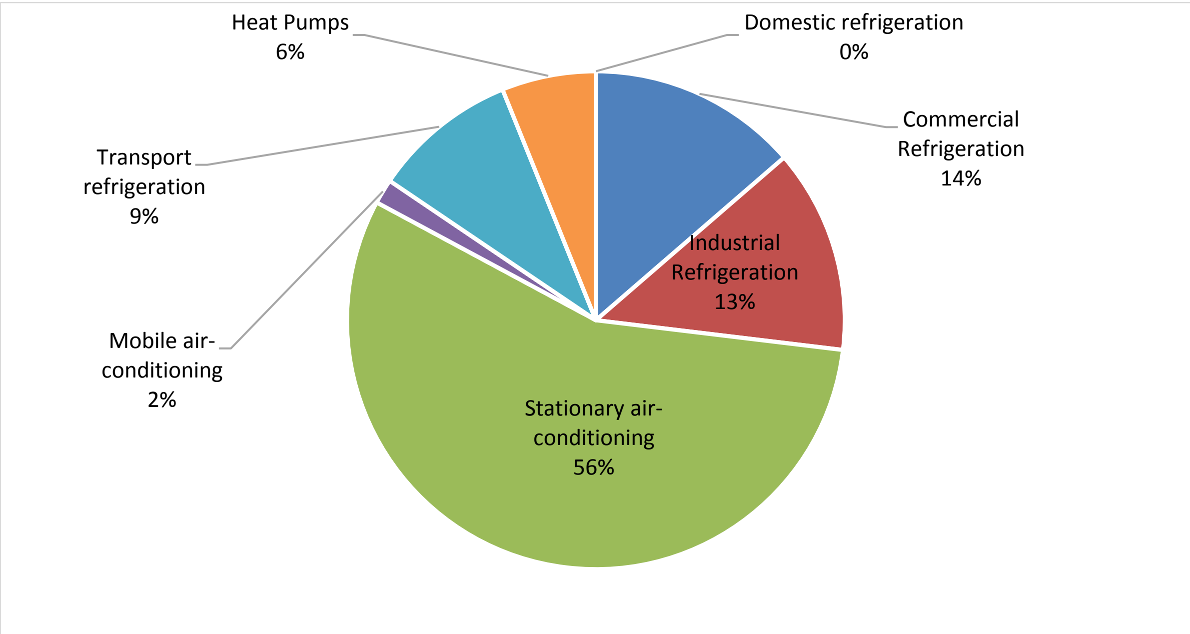
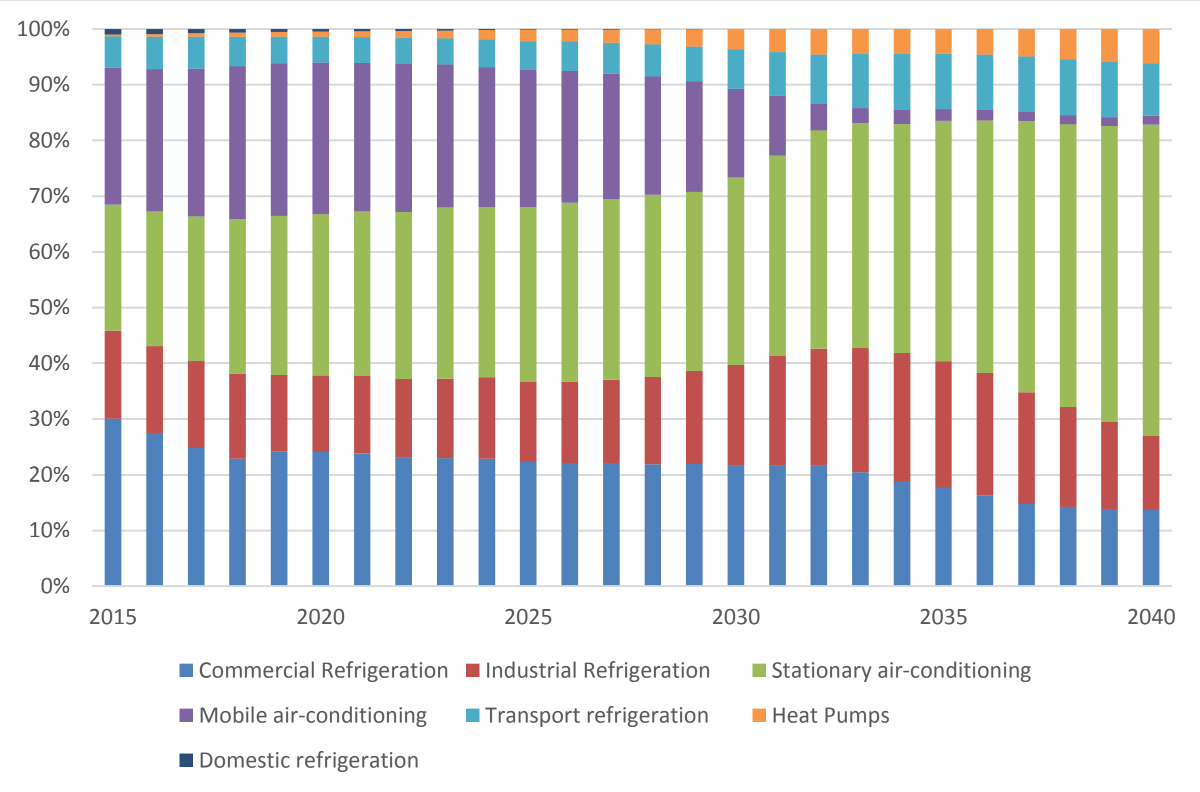


**Figure 3-10 Proportion of annual emissions, by RACHP Sector, 2015 to 2040**




This data shows that to reduce the residual amount of HFC consumption post-2040, the sector of greatest importance is stationary air-conditioning. There is also some potential for reducing emissions from heat pumps and commercial / industrial refrigeration. The reason that these sectors remain reliant on HFCs is related to the lack of availability of a low or ultra-low GWP refrigerant suited to the specific applications.

Figure 3-11 shows the trend in emissions by refrigerant. For most refrigerants there is a massive drop in emissions between 2015 and 2040. HFC-32 (and certain blends containing HFC-32 and HFOs) is the main refrigerant with growing emissions during this period. R-410A emissions fall substantially, but less than for R-404A and R-134a. This is seen more clearly in Figure 3-12 which shows the change in the mix of refrigerants emitted between 2015 and 2040. In 2015 R-404A and R-134a represented over 60% of HFC refrigerant emissions, with R-410A being the next most significant. By 2040 the use of R-404A and R-134a has dropped to a very small amount. HFC-32, various HFC/HFO blends and HFC-410A are expected to be the dominant HFC refrigerants emitted in 2040.

**Figure 3-11. Trend of RACHP HFC Emissions by Refrigerant**

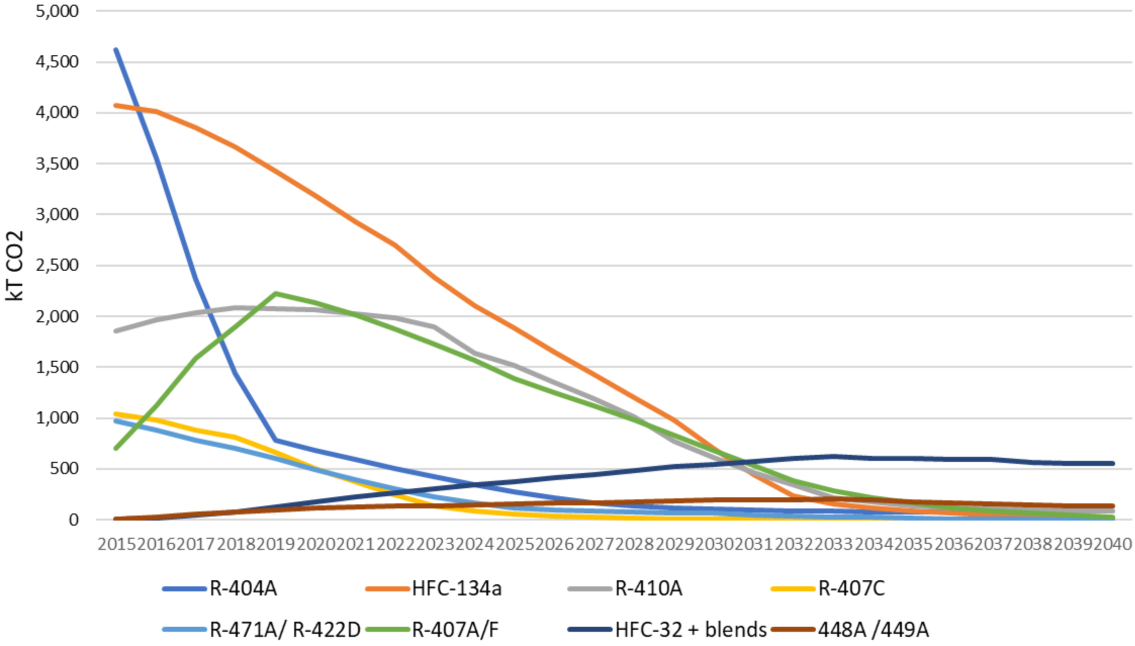
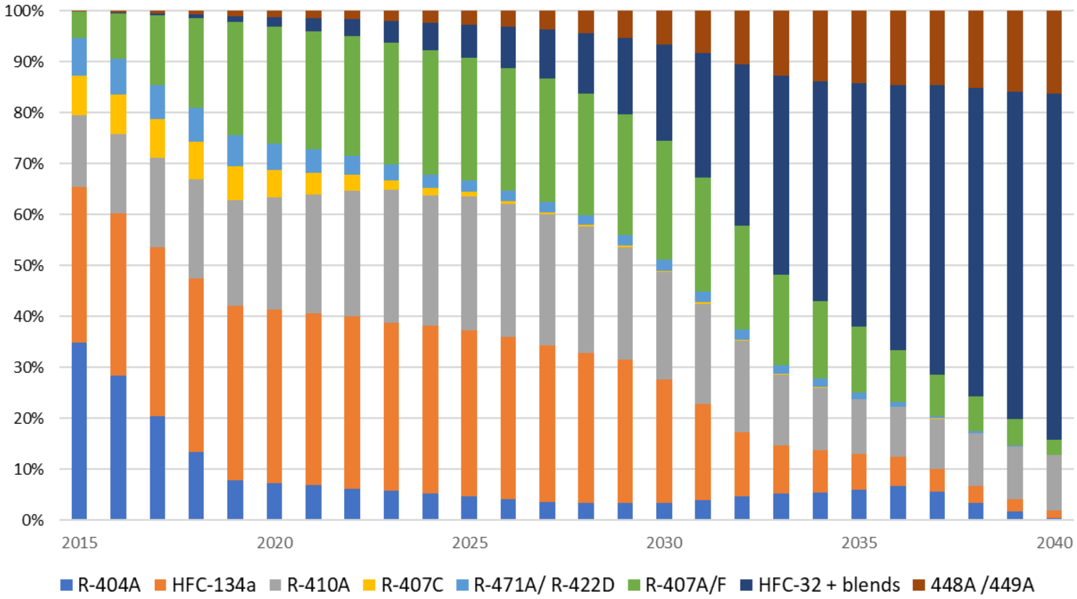



**Figure 3-12. Proportion of annual emission, by refrigerant**




Part of this trend is created by the refrigerant options available for small / medium sized air-conditioning and heat pumps. R-410A was the dominant refrigerant in these markets prior to 2015. It is worth noting that small and medium sized air-conditioning is mostly used in the commercial sectors (e.g. in shops, offices, hotels) with a small but growing use in residential applications. Heat pumps are mainly being introduced for residential space heating. The current technical options being adopted are:

a) If a non-flammable refrigerant is needed, e.g. for medium sized air-conditioning applications such as VRF systems used in hotels and offices, the stationary air-conditioning market **is still using R-410A.** With current safety regulations and attitudes to lower flammability (A2L) refrigerants the market is not yet showing any progress to move away from this refrigerant, and the RACHP emissions model assumes on-going use in new equipment to 2040 and beyond.

   **Technical potential:** the air-conditioning industry is currently investigating the possible use of A2L refrigerants in this sector of the market. Compared to just 2 years ago, the latest views are that current VRF systems can make use of A2L refrigerants in the future. There are two distinct technical options being developed:

**1)** Use of similar designs with "risk mitigation measures" to allow large VRF systems to operate safely.

**2)** Use of not-in-kind designs based on a hybrid system using chilled water in part of the system to eliminate flammability risk.

It is possible that one or both of these options will be commercially viable within the next 3 to 5 years. Adoption of these technologies will reduce the residual HFC requirements by approximately 50 kt $CO_{2eq}$ by 2040.

b) Where a lower flammability (A2L) refrigerant is acceptable, **the market is switching to HFC-32**. That is creating the growth in HFC-32 demand illustrated in Figure 3-11. HFC-32 has a GWP of 675. This is a significant reduction from R-410A (GWP 2088), but it does create a large proportion of the residual HFC emissions in 2040. Currently the industry is trying to switch to HFC-32 as quickly as possible. In the short-term this should be encouraged as HFC-32 not only has a reduced GWP but it also has better thermodynamic performance than R-410A, leading to the potential for improved energy efficiency (and reduced indirect $CO_2$ emissions).

**Technical potential:** currently there is little progress towards an HFC-32 alternative. For very small system charge, hydrocarbon refrigerants such as R-290 (propane) are a good option, but high flammability limits the proportion of the market that can use HCs. The current UK inventory modelling already allows for 10% of the small stationary air-conditioning market and 40% of the residential heat pump market to use HCs. It is possible that this proportion could be conservative, but it is unlikely that more than 25% of the small sized air-conditioning market and 50% of the residential heat pump market could use HCs. This increase in the use of HCs would reduce residual HFC requirements by approximately 80 kT $CO_{2eq}$ by 2040.

There is little likelihood of a refrigerant with similar properties to HFC-32 and a much lower GWP becoming available, so the industry would need to look for a not-in-kind design. One possibility would be to use the type of air-conditioning technology adopted in car air-conditioning – based on HFO-1234yf. This has a GWP of 4, which is a massive reduction. If this refrigerant could be adopted in place of HFC-32 in all small and medium split air-conditioning, the residual HFC requirements would be reduced by approximately 400 kT $CO_{2eq}$ by 2040. However, it must be stressed that the industry has not yet started developing systems of this type and it is not certain whether (a) they could achieve the same energy-efficiency level of HFC-32 equipment or (b) whether the switch of refrigerant can be cost-effective.

c) The RACHP emissions model currently assumes continuing use of non-flammable HFO/HFC blends such as R-448A and R-449A (GWP 1400) in small commercial, industrial and marine refrigeration sectors.

**Technical Potential**: There have been rapid developments during the last 2 years for lower GWP alternatives in these sectors. It is reasonable to expect that these markets could make much greater use of alternatives such as $CO_2$ (GWP 1) and lower flammability HFC/HFO blends (GWP ~150) from the early 2020s. This reduction in the use of non-flammable HFO/HFC blends would reduce residual HFC requirements by approximately 130 kT $CO_{2eq}$ by 2040.

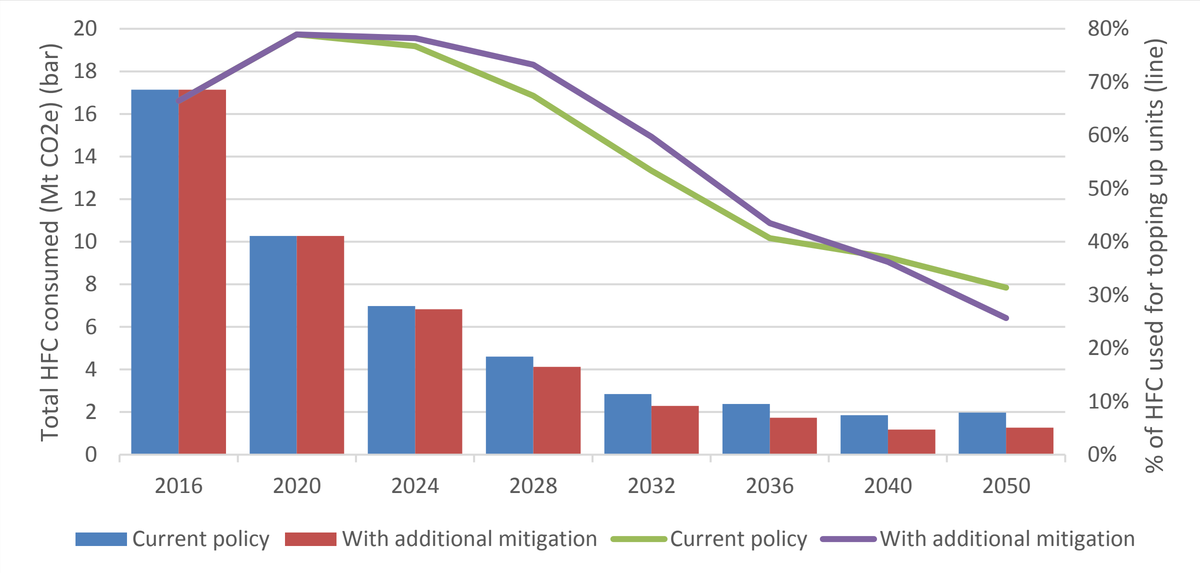
#### 3.4.2.2 Accelerating the switch to lower GWP gases, 2020 to 2030

Figure 3-4 shows the gradual drop in HFC emissions between now and the late 2030s. This decline is mainly driven by the gradual switch away from high GWP refrigerants in new equipment. The rate of switching is constrained mainly by the lifecycle of existing RACHP equipment. Figure 3-13 shows the part of the RACHP lifecycle that is most possible to influence, and one of the primary levers of EU F-gas regulations: HFC consumption. Note that the actual emissions of HFCs can occur many years after the initial consumption, so while it is possible to influence consumption, the impact on emissions would be observed over the following decade or two.

The graph illustrates that the majority of estimated HFC consumption in the near future is for the topping up of existing equipment; about 80% in 2020-24. This means that there is a significant limit to how much actions to reduce the use of HFCs in new equipment can have on the bank of HFCs and therefore emissions. The peak in the early 2020s is driven by the current EU F-gas regulations, having a strong impact on what HFCs can be used for new equipment. From the late 2030s, that the split between HFC demand for new units compared to topping up levels out; this reflects what the split would naturally reach without policy skewing the demand for new units.

The graph also shows the impact of all the mitigation options explored in Section 3.5. As expected, and similarly to the EU F-gas regulations, these mitigation options have a bigger impact on the demand for HFCs in new units, and therefore push up the proportion of HFCs used for topping up in the late 2020sand early 2030s.

**Figure 3-13. Estimated HFC consumption for RACHP, and the proportion of which is used for topping up equipment.**




In most RACHP market sectors there are already lower GWP alternatives available as illustrated in Table 3-3 and Table 3 4. A faster switch would require either:

a) Early retirement of existing equipment to enable early replacement with lower GWP gases. If the existing equipment is operating well and has good energy efficiency the extra costs related to early retirement would be very high. If the existing equipment has poor reliability or poor energy efficiency, then an early retirement may be more cost-effective. A simple estimate of the cost of abatement, not accounting for potential energy savings, found values in the range £300-1000 per tonne $CO_{2eq}$ abated for several major applications. These values are consistent with indications from the sector, and because these are prohibitively high costs of abatement we have not investigated these options in any further detail.

b) Retrofit of existing equipment with a lower GWP refrigerant. The RACHP emissions model already assumes significant retrofitting of the very high GWP refrigerant R-404A (GWP 3922) with alternatives with GWPs around 1400. Current recommendations are that retrofits of RACHP equipment designed for a non-flammable HFC refrigerant should only be carried out with a non-flammable lower GWP alternative. Further retrofit potential exists for:

    1) Small R-404A systems. Current assumptions about retrofits are for those systems affected by the F-Gas Regulation service ban which bans servicing of R-404A equipment containing more than 10 kg of refrigerant. It is possible that smaller

equipment in the transport refrigeration and commercial refrigeration sectors could be retrofitted. This has the potential to reduce the cumulative emissions between 2020 and 2040 by 1.3 MT $CO_{2\ eq}$.

2) R-134a systems. Some equipment using R-134a (GWP 1430) could be retrofitted with refrigerants including R-450A and R-513A (both with a GWP around 600). This has the potential to reduce the cumulative emissions between 2020 and 2040 by 1.2 MT $CO_{2\ eq}$.

3) R-410A systems. There will be a significant bank of R-410A equipment operating between now and 2030. Unfortunately, there is no non-flammable alternative currently available to retrofit these systems. Some new systems are switching to HFC-32 which has lower flammability (A2L). Designers have to take flammability into account to minimise safety risks. Using an A2L refrigerant for a R-410A retrofit is currently considered unsafe. However, it is possible that efforts could be made to investigate the possibility of R-410A retrofits.

#### 3.4.2.3 Further Reduction in Leakage Rates and Disposal Emissions

The Refrigerants Model already assumes that leakage rates from RACHP equipment will fall in response to the refrigerant shortages created by the HFC phase-down. Similarly, the emissions on equipment disposal at end-of-life is assumed to reduce. If the currently assumed leakage reductions are too conservative there is further potential for emissions reduction. End users would need to be encouraged to make more effort to avoid leakage and to be more vigilant about refrigerant recovery at end-of-life. As leakage leads to reduced energy efficiency it is possible that in some market sectors reduced leakage would save energy, providing extra $CO_2$ emission reductions and financial savings to offset the cost of leakage reduction initiatives. It is unlikely that leakage emissions can be improved in sectors using large numbers of small items of equipment (e.g. stand-alone commercial refrigeration, small building air-conditioning, residential heat pumps. However, there could be potential for large commercial refrigeration (supermarkets) and industrial refrigeration. Through a combination of improved equipment design and improved technician skills, the currently projected leakage rates in these sectors could improve by 5% by 2020, rising to 20% by 2035. This has the potential to reduce the integrated emissions between 2020 and 2040 by 2.4 MT $CO_{2\ eq}$.

## 3.5 Abatement Costs

The technical potential for reducing RACHP emissions at a faster rate than under current policies was described in Section 3.4.

With current policies, total RACHP emissions in 2040 are forecast to be 0.87 MT $CO_{2eq}$ and cumulative emissions between 2020 and 2040 are forecast at 80 MT $CO_{2eq}$. As shown in Figure 3-4, the rate of fall in emissions under current policies is fast during the 2020s. The cumulative emissions in the decade 2020 to 2029 are forecast to be 63 MT $CO_{2eq}$ whereas emissions between 2030 and 2039 are only forecast to be 16 MT $CO_{2eq}$.

Table 3-5 summarises the various technical measures that have potential to reduce the emissions from current RACHP policy projections. These measures only have a small impact on the cumulative emissions between 2020 and 2040, but have a fairly significant impact on the level of emissions in 2040 (an approximate 35% reduction).

**Table 3-5: Possible RACHP Emission Reductions Beyond Current Policy Forecasts**

| Measure | 2040 emission reduction MT $CO_2$eq | % of 2040 RACHP emissions | Cumulative emission reduction 2020 to 2040 MT $CO_2$eq |
|---|---|---|---|
| 1. Reduced use of R-410A in medium sized air-conditioning using alternative HFC-32 based technologies. | 0.03 | 3% | 0.2 |
| 2. More use of propane refrigerant in very small air-conditioning (instead of HFC-32) | 0.05 | 5% | 0.3 |
| 3. Reduced use of R-448A and R-449A in small commercial, industrial and marine refrigeration (using A2L blends or $CO_2$) | 0.20 | 22% | 1.9 |
| 4. Retrofit of small R-404A equipment | - | - | 1.3 |
| 5. Retrofit of some R-134a equipment | - | - | 1.2 |
| 6. Leak reductions through improved design and maintenance | 0.04 | 5% | 2.4 |

If a refrigerant such as HFO-1234yf could be used in place of HFC-32 for small and medium sized air-conditioning, the reduction of emissions would be around 1.2 MT $CO_{2eq}$ (approximately 50% of residual emissions up to 2040. However, we have not collected any evidence to be confident that this is a feasible or cost-effective measure. Given the significant scale of the possible emission reduction we recommend that CCC do further investigation into this issue.

### 3.5.1 Cost Implications

The possible cost impact of the measures listed in Table 3-5 is as below. Projected electricity costs are based on BEIS' Energy and Emissions Projections. The electricity carbon intensity is calculated based on the projected fuel mix from BEIS' Energy and Emissions Projections and the implied emission rate of each of those fuels for 2016 using UK NAEI emissions data.

**Measure 1: reduced use of R-410A in medium sized air-conditioning**. The key technology is VRF air-conditioning systems. These are used in multi-room air-conditioning systems such as in medium sized hotels and office buildings. The most likely technologies to be adopted are HFC-32 VRF systems with risk mitigation measures or hybrid HFC-32 VRF systems using chilled water. It is estimated that around 5,000 VRF installations per year might be affected. The risk mitigation measures include addition of new components including a leak detector in each room together with extra controls such as shut-off valves and automatic fan switching. It is estimated that such technology could add between £500 and £1500 per 10 room VRF installation. These costs will be offset by a small increase in energy efficiency as HFC-32 VRF systems will be slightly more efficient than R-410A systems. Over the 15-year life of a VRF unit the energy saving could be in the range of £2,000 to £4,000. Hence this measure has an abatement cost below zero. The emissions saving of 0.2 MT $CO_{2eq}$ until 2040 for this F-Gas emission reduction is supplemented by a further 0.1 to 0.2 MT $CO_2$ until 2040 for the electricity savings.

**Measure 2: greater use of propane split air-conditioning**. The RACHP emissions model assumes 10% of small split air-conditioning units use propane, from around 2023. Under this measure, the number of propane units rise to 25% of new units by 2027. The units will potentially increase slightly in cost because of the need for extra risk mitigation measures (e.g. design measures for leak prevention and to protect electrical contacts from propane vapour if a leak occurs). Propane units have the potential to be very energy efficient. The estimated emissions saving of 0.3 MT $CO_{2eq}$ up to 2040 for this F-Gas emission reduction is supplemented by a further 0.04 to 0.09 MT $CO_2$ until 2040 for the electricity savings. Assuming an extra cost of between £50 and £100 per installation and 50,000 installations per year this does not offset the savings made in reduced energy costs.

**Measure 3: reduced use of non-flammable HFO/HFC blends in small commercial, industrial and marine refrigeration**. Currently small and medium sized refrigeration installations in these sectors use a significant amount of the non-flammable refrigerant R-404A (GWP 3922). The RACHP emissions model assumes a significant switch to non-flammable HFO/HFC blends[10] in new equipment during the period 2016 to 2025 and a small continuing use of these non-flammable HFO/HFC blends beyond 2040. During the last year, good progress has been being made in the development of small condensing units using either R-744 ($CO_2$) or lower flammability (A2L) HFO/HFC blends with GWPs around 150. These units are currently slightly more expensive than equipment using the non-flammable HFO/HFC blends, but costs are rapidly falling. Assuming extra costs of:

- £100 to £200 for small retail condensing units
- £500 to £1500 for small industrial systems
- £2000 to £4000 for small marine systems

the overall cost of abatement is estimated to be between £0.2 and £0.4 per tonne $CO_{2eq}$ saved up to 2040. It is not expected that there are any energy savings that could mitigate these costs.

**Measure 4: Retrofit of small R-404A equipment**. Retrofitting of R-404A systems will be required for larger systems due to the ban on servicing of R-404A systems containing more than 10 kg. The RACHP model already assumes that this retrofitting will take place. There is a significant number of smaller condensing unit systems and refrigerated road transport units that will still be using R-404A between 2020 and 2030. After 2030 the emissions of R-404A rapidly fall to zero, as very few new R-404A systems have been installed after 2016. It is possible that a proportion of the smaller systems will be retrofitted with non-flammable alternatives such as R-448A, R-449A (GWP 1400) and R-452A (GWP 2140). When the service ban was evaluated by the European Commission in 2013, it was not thought that retrofitting small units (<10 kg) would be cost effective. This situation has changed for two reasons: (a) retrofits to the 3 gases listed above have proved to be technically easier than expected – and hence less expensive and (b) the price of R-404A has risen much faster than expected (from £10 per kg in 2016 to £100 per kg in 2018). The net cost of retrofitting a small system is estimated to be around £100 to £200. The retrofit is likely to create between 2.5% and 5% energy efficiency improvement – which offsets the cost of the retrofit, making this mitigation a cost benefit. The emissions saving of 1.3 MT $CO_{2eq}$ until 2040 for this F-Gas emission reduction is supplemented by a further 0.5 to 1.1 MT $CO_2$ for the electricity savings.

**Measure 5: Retrofit of R-134a equipment**. R-134a (GWP 1430) is used in several sectors including commercial refrigeration, industrial refrigeration and water chillers. Under current policies there is no retrofitting of R-134a systems assumed. This situation could change from 2021 when the next big HFC phase-down cut occurs and puts greater price pressure on R-134a. Refrigerants such as R-450A and R-513A (GWP 600) can be used to retrofit some of the systems currently using R-134a. It is expected that the technical methodology to be used will be like that on the retrofits of R-404A described under measure 4. The cost effectiveness will not be as good as for R-404A as the GWP of R-134a is much lower, so there is less emission reduction per retrofit, and there is also much more uncertainty about the cost of these retrofits as they are not currently being conducted. The overall cost of abatement might be in the range of £20 to £60 per tonne $CO_2$ saved.

**Measure 6: Leak reductions through improved design and maintenance**. The RACHP model assumes significant improvement in leak rates during the period 2010 to 2020 and further small

[10] -448A / R-449A (GWP 1400); and R-450A / R-513A (GWP 600)

improvements between 2020 and 2030. Improving the leak rates further can be achieved by a combination of better equipment design and better maintenance of existing systems. With refrigerant prices rising steeply in response to the HFC phase-down it is reasonable to expect greater improvements in this area. The extra costs of leakage reduction efforts are offset by energy savings, as refrigerant leakage leads to a loss of efficiency. The emissions saving of 2.4 MT $CO_{2eq}$ up to 2040 for this F-Gas emission reduction is supplemented by a further 1.5 to 3 MT $CO_2$ for the electricity savings till 2040.

**Table 3-6: Cost of Abatement Summary**

| Measure | Cumulative emission reduction 2020 to 2040 MT $CO_2$eq | | Cost of abatement £ per tonne $CO_2$ saved | |
|---|---|---|---|---|
| | F-Gas | Electricity | Low estimate | High Estimate |
| 1. Reduced use of R-410A in medium sized air-conditioning using alternative HFC-32 based technologies. | 0.2 | 0.1 | Negative cost | |
| 2. More use of propane refrigerant in very small air-conditioning (instead of HFC-32) | 0.3 | 0.1 | Negative cost | |
| 3. Reduced use of R-448A and R-449A in small commercial, industrial and marine refrigeration (using A2L blends or $CO_2$) | 1.9 | - | 0.2 | 0.4 |
| 4. Retrofit of small R-404A equipment | 1.3 | 0.8 | Negative cost | |
| 5. Retrofit of R-134a equipment | 1.2 | - | 20 | 60 |
| 6. Leak reductions through improved design and maintenance | 2.4 | 2.2 | Negative cost | |

# 4 Enhanced mitigation options for Metered Dose Inhalers (MDIs)

## 4.1 Background

MDIs are medical aerosols used for administering certain drugs directly into a patient's lungs. They were first introduced in the 1950s and are widely used globally for the treatment of various lung diseases, in particular asthma and COPD (chronic obstructive pulmonary disease).

MDIs used CFC propellants until the phase-out of CFCs that started in the 1990s. The CFC propellants were replaced with HFCs – mainly HFC-134a and some HFC-227ea. The replacement process was lengthy and expensive because of the need for extensive testing of:

- the toxicity of the propellant
- the toxicity and efficacy of specific propellant / drug formulations.

The switch from CFCs to HFCs took over 10 years to achieve and MDIs were given special exemptions during the phase-out of CFCs under the Montreal Protocol. HFCs have been used in all MDIs sold in the UK (and most developed countries) since 2009. Progress has been slower in developing countries, with the final phase-out of CFC MDIs in around 2016.

Any mitigation options considered need to maintain medical outcomes.

## 4.2 Current UK Use and Emissions

UK emissions from MDIs are estimated using prescription data published by the NHS on an annual basis. MDIs are an emissive application of HFCs and it is assumed that the propellant used in each MDI prescribed is emitted to the atmosphere within one year.

In 2016 it was estimated that UK F-Gas emissions from MDIs were 1.0 million tonnes $CO_2$ equivalent, based on a usage of 54 million MDIs[11]. This was approximately 6% of total UK F-Gas emissions in 2016.

## 4.3 Emissions Projections, 5th Carbon Budget Period

The current EU F-Gas Regulation[12] exempts MDIs from the EU HFC phase-down, hence there are no direct regulatory pressures on this application of HFCs.

The use of MDIs has risen steadily over recent years. Around 40 million MDIs were prescribed in the UK in 2006, rising by 35% to reach the level of 54 million in 2016. This increase is at a considerably higher rate than the growth in population, which rose by 8% during the same period.

It is expected that without any change to the current prescribing practices usage and emissions will continue to rise slowly. The UK population is forecast to have risen a further 8% by 2030[13]. A conservative estimate is a further 10% rise of MDI use by 2030, leading to a projected emission of 1.1 MT $CO_2$eq. It is forecast that MDIs will represent over 25% of UK F-Gas emissions during the 5$^{th}$ carbon budget period.

[11] UK Greenhouse Gas Emissions Inventory
[12] EU Regulation 517/2014 on fluorinated greenhouse gases
[13] ONS, National Population Projections: 2014-based Statistical Bulletin

# 4.4 F-gas alternatives

## 4.4.1 Low GWP Alternatives

There are low GWP alternatives that could replace a significant proportion of current MDI usage and have the potential to cut emissions by over 90% by the 5th carbon budget period. The two main options available are:

- Dry powder inhalers (DPIs), a not-in-kind alternative to MDIs
- MDIs using a low GWP propellant.

In addition to these main options there is also some use of nebulisers and other aqueous spray inhalation devices, but these represent a relatively small part of the market.

### 4.4.1.1 Dry Powder Inhalers

DPIs are widely available and in many countries they are already used for a far greater proportion of inhaled lung medications that in the UK (see section 4.6.1 for further discussion). During the last 10 years the technologies for dispensing multi-dose DPIs have developed rapidly and they represent a sophisticated and mature technology. The main barriers to a greater uptake of DPIs are (a) perceived cost issues and (b) lack of awareness amongst GPs and patients. If these barriers could be overcome, DPIs could take a significant share of the current MDI market well before 2028.

### 4.4.1.2 Low GWP MDI propellants

Various new propellants are being tested for use in MDIs. The GWPs of several propellants are shown in Table 4-1. The current main propellant (representing an estimated 96% of UK MDIs) is HFC-134a. The remaining 4% of current generation MDIs use HFC-227ea.

**Table 4-1: GWPs[14] of MDI propellants**

| Category | Propellant | GWP |
|---|---|---|
| Last generation | CFC-12 | 10,900 |
| Current generation | HFC-134a | 1,430 |
| | HFC-227ea | 3,220 |
| Being considered / developed | HFC-152a | 124 |
| | HFO-1234ze | 7 |
| | HC-600a | 3 |

Both of the current generation propellants have high GWPs (albeit not as high as the old CFC propellants).

The development of HFC-152a is at the most advanced stage, with around 3 years of test work completed and the early tests show encouraging results. The development work is led by Mexichem which is the world's leading supplier of pharmaceutical grade HFCs. If all MDIs could switch to HFC-152a there would be a cut in $CO_2$ emissions of over 90%. The cut in emissions would be even higher if HFO-1234ze or HC-600a (iso-butane) were used. These propellants are at an earlier stage of development than HFC-152a.

The main barriers to the uptake of low GWP propellants are (a) the cost of product development and (b) the lengthy timescale before new products are likely to be fully approved. Whilst DPIs could replace MDIs used in the UK quite quickly (e.g. over a 3 to 5 year period), the introduction of low GWP propellants is likely to take a further 6 to 10 years. If these barriers could be overcome, the majority of current generation MDIs could be replaced with low GWP MDIs by 2028.

[14] All GWPs in this report are 100-year values from the 4th Assessment Report of the IPCC. These are the values used in the 2014 EU F-Gas Regulation.

### 4.4.2 Carbon Footprint Assessment

A recently published study[15] presents a life cycle assessment (LCA) of three alternative modes of delivering inhaled drugs:

- a current generation MDI, using HFC-134a propellant
- a typical current generation DPI
- a future MDI using HFC-152a propellant.

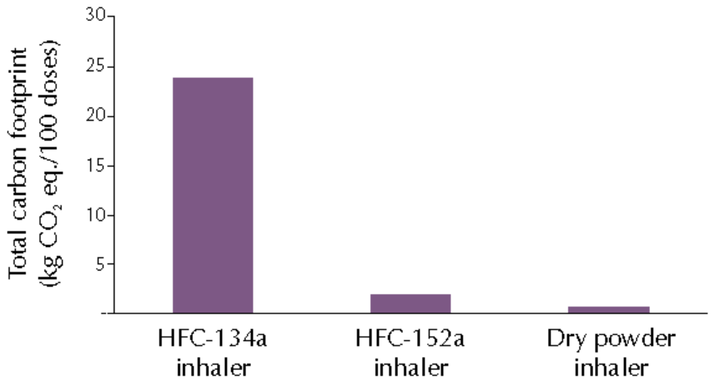
The figure below summarises the results of the LCA in terms of life cycle greenhouse gas emissions. It should be noted that the study did not include the carbon footprint of the active drug being dispensed – the study was aimed at showing the difference in the carbon footprint of the delivery systems.

For the current generation MDI, 99% of the emissions are from the HFC-134a propellant. For a low GWP HFC-152a MDI, the propellant emissions are still dominant (89%) but at a significantly lower level. The DPI has no propellant emissions; the majority of the emissions (91%) are from the raw materials used (mainly plastics) and in the production process.

The reduction in F-Gas emissions is clearly very significant. Based on the data in Figure 4-1, the reduction for using DPIs is 100% and for using an HFC-152a MDI is 93%.

The study used outdated GWP values for both HFC-134a and HFC-152a (of 1,300 and 140 respectively). As shown in Table 4-1, the GWP estimate used in the EU F-Gas Regulation is higher for HFC-134a and lower for HFC-152a. If the study used these values the HFC-134a propellant emissions rise to 25.74 kg $CO_2$ per 100 doses and the HFC-152a emissions fall to 1.45. This is an F-Gas emission reduction of 94%.

**Figure 4-1. Comparison of the carbon footprints of inhalers**




| **Total carbon footprint** | **23.65** | **1.80** | **0.65** |
|---|---|---|---|
| Waste disposal | 0.01 | 0.01 | 0.04 |
| Use (propellant emissions) | 23.40 | 1.61 | — |
| Transport | 0.01 | 0.01 | 0.02 |
| Production | 0.06 | 0.03 | 0.13 |
| Raw materials | 0.17 | 0.13 | 0.46 |

## 4.5 Projections

If the barriers to the use of DPIs and low GWP MDIs (described in Section 4.4 and detailed in Section 4.7) can be overcome, a credible future scenario is that the use of all current generation MDIs will switch to either DPIs or to low GWP MDIs.

[15] Inhalation Magazine, December 2015, Reducing Carbon Footprints of MDIs, Study by Manchester University and Mexichem

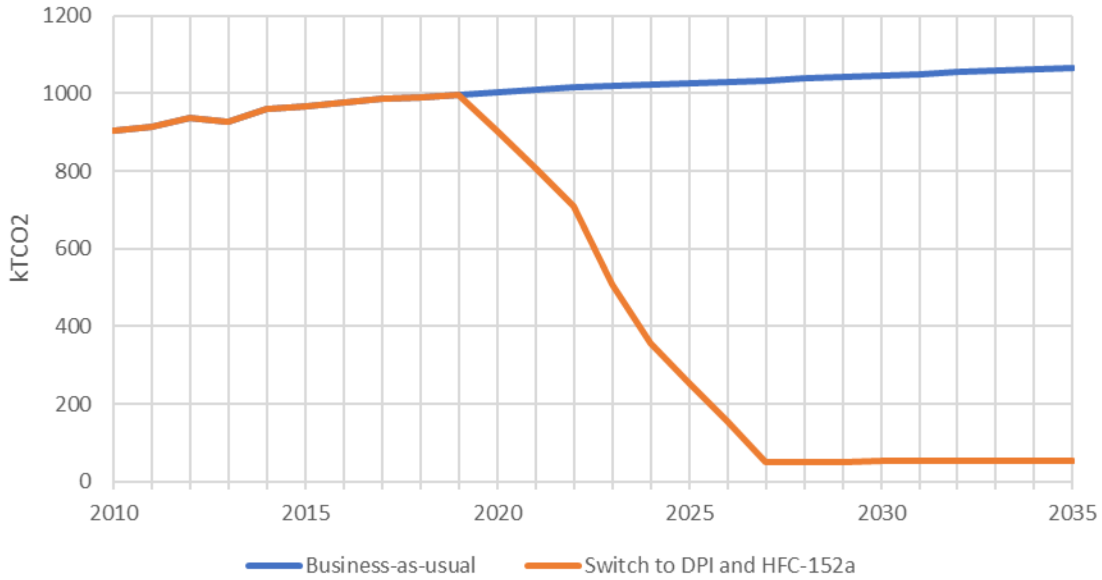
The switch to DPIs could take place relatively quickly (over the next 3 to 5 years), whereas a switch to low GWP MDIs will take longer (6 to 10 years). By the start of the 5th carbon budget period in 2028 a transition to either of these options could be complete.

Which of the two low carbon footprint technologies will become dominant? This is a complex issue based on a combination of financial and medical issues, which are further discussed below. Based on the research carried out during this project it is believed that there is an important role for both technologies. The development of the markets for both DPIs and low GWP MDIs should be encouraged to maximise the availability of effective treatments that suit the whole patient population.

Figure 4-2 illustrates a possible projection of future emissions, based on a 50% split between the use of DPIs and low GWP MDIs by 2027. It is assumed that the switch to 50% DPIs occurs linearly from 2020 to 2024 and the switch to 50% HFC-152a MDIs occurs linearly between 2023 and 2027.

By the end of the 5th carbon budget period the annual emission reduction is 1.0 million tonnes $CO_2$. The cumulative reductions from 2020 to 2032, compared to business-as-usual is estimated to be 9.4 million tonnes $CO_{2eq}$.

**Figure 4-2. Forecast of technical potential for MDI Emissions**




# 4.6 Additional information

## 4.6.1 National variations in MDI / DPI Usage

There is a surprising variation in the split between MDI, DPI and nebuliser administered lung treatments in different countries in Europe. Figure 4-3 is an extract from a paper[16] that analysed the retail sales of inhaled lung treatments during the 7-year period 2002 to 2008. This shows that for the UK, around 75% of total sales are MDIs. This compares to an average of only 47% for all 16 countries in the study and under 10% for Sweden.

The UK is a clear outlier, with considerably higher MDI usage than any of the other countries in the study. The UK consistently uses more MDIs for the four main categories of drugs, as illustrated in

[16] Respiratory Medicine, 2011, Retail sales of inhalation devices in European countries

Figure 4-4. The reasons for such high MDI use seem to be linked to the prescribing habits of GPs and the familiarity of MDIs for both patients and GPs.

**Figure 4-3. Comparison of Lung Treatment Device Sales: Total Sales**

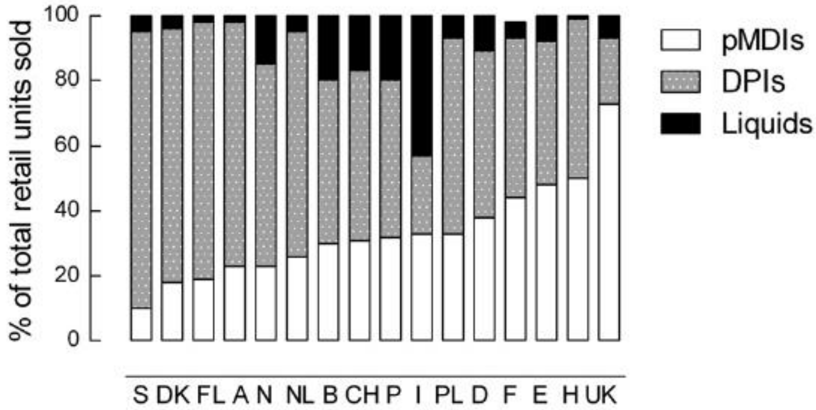
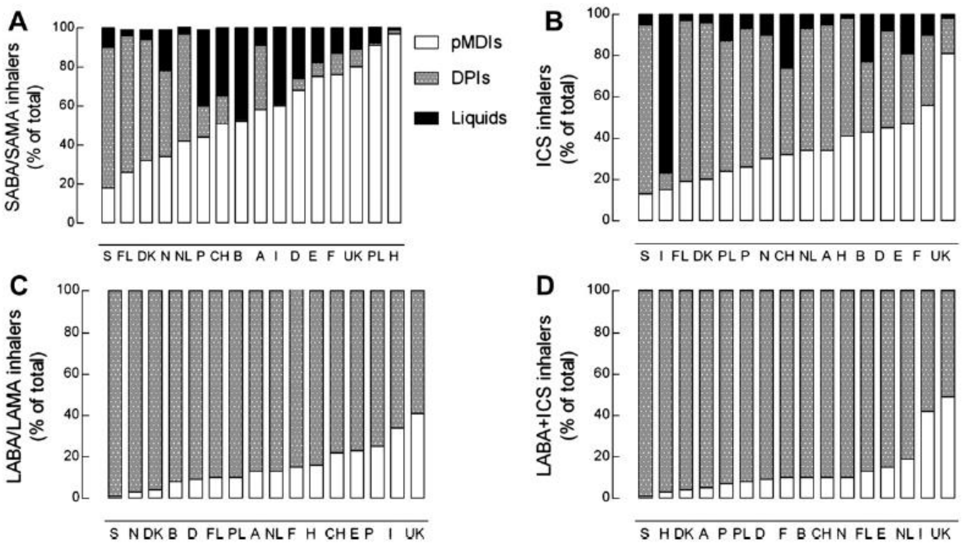



**Figure 4-4. Comparison of Lung Treatment Device Sales: Split by Drug Category**




SABA / SAMA: short-acting beta-agonist and antimuscarinic bronchodilators

LABA / LAMA: long-acting beta-agonist and anti-muscarinic bronchodilators

ICS: inhaled corticosteroids

LABA + ICS: combination treatments

## 4.6.2 Price Comparisons

The price paid by the NHS for most drugs is made available to doctors in the BNF (British National Formulary) which is published every 6 months by the British Medical Association and the Royal Pharmaceutical Society. Monthly updates are available on-line. Prices shown below are from the on-line NHS Drug Tariff, April 2018.

| Table 4-2 Example Drug Prices, April 2018 | | | | |
|---|---|---|---|---|
| **SABA** (short-acting beta-agonist, used several times per day as a "rescue" inhaler) | | | Price 2018 | Thousands sold 2016 |
| Salbutamol | 100 mcg, 200 doses | MDI | 1.50 | 33,510 |
| | | Breath actuated MDI | 6.30 | |

| Table 4-2 Example Drug Prices, April 2018 | | | | |
|---|---|---|---|---|
| | | DPI | 3.31 | 1,367 |
| Terbutaline sulphate | 500 mcg, 100 doses | MDI | n/a | |
| | | DPI | 8.30 | 1,174 |
| **ICS** (inhaled corticosteroids, used once or twice per day as preventative medicine) | | | | |
| Beclometasone dipropionate | 50 mcg, 200 doses | MDI | 5.13 | 1,810 |
| | | DPI | 5.43 | 0.1 |
| | 100 mcg, 200 doses | MDI | 9.66 | 5,512 |
| | | DPI | 9.83 | 9 |
| | 200 mcg, 200 doses | MDI | 16.17 | 1060 |
| | | DPI | 14.93 | 51 |
| Budesonide | 200 mcg, 100 doses | MDI | n/a | |
| | | DPI (manufacturer 1) | 11.84 | 1,211 |
| | | DPI (manufacturer 2) | 14.86 | |
| Fluticasone propionate | 125 mcg, 120 doses | MDI | 21.26 | 413 |
| | 100 mcg, 60 doses | DPI | 10.72 | 192 |
| **LABA** (long-acting beta-agonist, used with ICS once or twice per day) | | | | |
| Formoterol fumarate | 12 mcg, 100 doses | MDI | 30.06 | 47 |
| | 12 mcg, 120 doses | DPI (manufacturer 1) | 23.75 | 235 |
| | 12 mcg, 60 doses | DPI (manufacturer 2) | 28.06 | |
| | 12 mcg, 60 doses | DPI (manufacturer 3) | 24.80 | |
| Salmeterol | 50 mcg, 60 doses | MDI | 29.26 | 765 |
| | | DPI | 35.11 | 190 |
| **Compound drugs** (LABA + ICS in one inhaler, used once or twice per day) | | | | |
| Formoterol fumarate + Beclometasone dipropionate | 6 mg + 200 mcg 120 doses | MDI | 29.32 | 3,811 |
| | | DPI | 29.32 | 9 |
| Salmeterol + Fluticasone propionate | 50 mg + 250 mcg 60 doses | MDI | 35.00 | 5,192 |
| | | DPI | 35.00 | 3,711 |

Salbutamol is the most widely prescribed inhaled drug. Around 33 million are sold as MDIs and only 1.4 million as a DPI. The MDI price is very low – at £1.50 for 200 doses the cost is less than 1p per dose, which is probably lower than almost any other prescribed drug. The DPI version is around twice the price. It is interesting to note that a breath actuated MDI is four times the price of an ordinary MDI – this type of MDI is used by patients that find the coordination required to effectively use an ordinary MDI too difficult.

Beclometasone dipropionate is the most widely used ICS (corticosteroid). As shown above, comparing the prices of DPIs to MDIs is complicated by the different doses, and this is complicated further by the fact that many of the more expensive MDIs are breath-actuated. Note that less than 1% of 8.7 million UK prescriptions for this drug were DPIs (in 2016).

Fluticasone propionate is an alternative ICS drug. Despite approximately equal prices around 70% are sold as MDIs.

Budesonide is also a widely used ICS. It is only available as a DPI, with over 1 million being used in 2016.

The LABA drug formoterol fumarate is the only one available as both an MDI and a DPI that is used significantly more widely as a DPI (0.235 million versus 0.047 million). It is also interesting to note that the DPI price is cheaper than the MDI from one manufacturer but that other DPIs are considerably more expensive for the same dose.

There are a significant number of compound LABA / ICS drugs prescribed. These simplify treatment for a patient as they only need to use one inhaler to get two different drug treatments. Out of eight compound treatments quoted in the BNF, five are only available as DPIs. Two examples of compound drugs available in both formats are shown in Table 4-2. In both cases the prices are identical for equivalent dosages. For formoterol fumarate + beclometasone dipropionate MDIs are dominant (over 99% of sales) whereas for salmeterol + fluticasone propionate DPIs hold around 40% of sales.

### 4.6.3 Factors influencing a financial comparison of MDIs and DPIs

It is not a simple process to estimate the cost per tonne $CO_2$ saved by switching between MDIs and DPIs. As discussed in Section 4.6.2 and illustrated in Table 4-2, for some inhaled drugs there are no price differences. For the most popular drug (salbutamol) the price difference is significant. But the purchase price is not the only factor to consider. Several other important issues must be taken into account:

#### 4.6.3.1 Proficiency of MDI Use

Drug trials show that MDIs and DPIs are medically equally effective. However, before a drug trial is carried out, the patients are selected and trained to ensure that they can use the MDI or DPI with a high level of proficiency.

“Real life” studies have shown that for many patients MDIs are more difficult to use than DPIs. MDIs require careful coordination of aerosol actuation with an intake of breath. If this is not done correctly much of the drug is wasted. DPIs are actuated by the intake of breath, so coordination is not required, and effective use is easier to achieve. Breath actuated MDIs can also avoid this problem, but as indicated in Table 2, these can be considerably more expensive than ordinary MDIs or DPIs. The use of an MDI with a spacer also avoids this problem, but as spacers are relatively cumbersome they are only used in special circumstances (see next section on compatibility).

The Salford Lung Study[17] compared the use of a once per day DPI compound drug treatment with “usual treatment” including use of MDIs. In a real world setting it was found that around 50% of MDI users were not using their inhalers correctly whereas only 10% were using DPIs incorrectly.

#### 4.6.3.2 Patient compatibility with DPIs

As the use of a DPI requires a fairly sharp intake of breath, there is a small proportion of patients that find them difficult or impossible to use. In particular very old and very young patients and those suffering a severe acute respiratory episode. This probably affects less than 10% of all patients (as illustrated by the 90% use of DPIs in Sweden). This group of patients will also find the MDI actuation coordination a problem and must use an MDI with a spacer.

The fact that some patients need an MDI supports the requirement to have both MDIs and DPIs available in the long term, but does not support the UK’s high usage of MDIs.

[17] Pragmatic and Observational Research. 2017; The Salford Lung Study: a pioneering comparative effectiveness approach to COPD and asthma in clinical trials

#### 4.6.3.3 Rescue drugs versus preventative treatment

The cheapest drug is salbutamol and this is considered a “rescue drug” that might be used frequently during the day to alleviate symptoms. Salbutamol is a short acting drug. Many of the other drugs available are long-acting and are usually used only once per day and work as a preventative therapy. Although the drug price might be considerably higher than salbutamol, less doses are likely to be required.

#### 4.6.3.4 Medical effectiveness

An important consideration for health professionals is the overall cost of controlling and treating a disease. If a cheap treatment leads to a greater number of severe acute respiratory episodes these may require much more expensive medical interventions including emergency ambulance services and treatment in hospital. By using the most effective preventative treatment such episodes are minimised and the overall cost reduced even if the basic drug is more expensive.

#### 4.6.3.5 Wastage on disposal

Most MDIs are sold in 200-dose disposable aerosols. There is no counter to help patients judge when the MDI is nearly empty. Evidence from an MDI recycling scheme shows that some patients are quite cautious – they don’t want their MDI to run out, so they dispose of the MDI before it is completely empty. This could mean that around 20% of doses are wasted, which makes the real price of an MDI 20% higher.

Some MDIs are prescribed but hardly used at all and are disposed of nearly full. The HFC emissions would be avoided if MDIs were sent to a specialised recycling centre, but it is believed that less than 5% of MDIs are disposed of through such facilities.

#### 4.6.3.6 Prescription charges

All inhaled drugs delivered by MDIs and DPIs are prescription-only medicines. The current prescription charge is £8.80. If a patient has to pay the prescription charge then any prescription for a drug costing less than £8.80 will cost the patient the same full amount. Hence the difference between the MDI and DPI price for salbutamol is not relevant to the patient.

#### 4.6.3.7 Summary comments

The various considerations described above indicate how difficult it is to use the price per item as a way of estimating the marginal abatement cost of a switch from MDIs to DPIs. The various issues indicate that for MDIs that are cheaper to prescribe than an equivalent DPI, the actual cost difference is likely to be considerably lower.

NICE provide guidelines to UK GPs and other doctors about the best treatment regime for asthma and COPD. Work carried out around 10 years ago indicated that MDIs were cheaper but that cost differences were not sufficiently large to influence the doctor’s choice of the best treatment regime. Since that work was done many new DPIs have been introduced and the technology for multi-dose DPIs has matured and costs have reduced. NICE are currently reviewing this area.

## 4.7 Abatement Costs

In this section we review the marginal abatement cost, in terms of £ per tonne $CO_2$ saved, for the use of either DPIs or low GWP MDIs.

### 4.7.1 Using DPIs

DPIs are already widely available and used for a much greater proportion of lung treatment in most EU countries. Hence there are no product development costs that need to be taken into account. The marginal abatement costs switch from MDIs to DPIs can be assessed by reviewing:

a) The tonnes $CO_2$ saved created by the switch.

b) The current price difference between equivalent devices (as summarised in Table 4-2)

c) The possible modification of the price difference to take into account the mitigating factors described in Section 4.6.2.

d) The possible modification of the price difference to account for larger volume sales of certain DPIs.

***Environmental benefits:*** As illustrated in Section 4.5, the F-Gas emission reduction for a switch from MDIs to DPIs is 100%. The cut in total carbon footprint is slightly lower (97%) due extra manufacturing emissions for DPIs. If all MDIs switched to DPIs, the F-Gas emission savings would be 1.1 million tonnes $CO_2$ per year during the 5th carbon budget period.

***Price increment salbutamol:*** Salbutamol represents 61% of all MDI sales, hence is a very important consideration in the marginal abatement cost analysis. As shown in Table 4-2, the cost increment per 200-dose inhaler is around £1.80.

Note that we are assuming that breath-actuated MDIs will not be replaced with DPIs because it is likely that there are medial or personal preference reasons for using the more expensive medication. DPIs are, in general, significantly cheaper than breath-actuated MDIs.

Note further that some DPIs allow users to purchase refills instead at a much lower price (£2.75), although in 2016 not many refills were used in comparison to new inhalers. If there were a shift to using refills more often this would reduce the price increment by up to almost a 1/3.

***Abatement cost, salbutamol:*** Emissions are around 50 kg $CO_{2eq}$ per 200-dose inhaler. This makes the marginal abatement cost £100 per tonne $CO_2$ saved. This should be considered as the worst-case cost of abatement. Allowing for more effective use of DPIs by patients, less product wastage at end-of-life and larger volumes sold it is estimated that the marginal abatement cost would be significantly lower.

***Price increment beclometasone dipropionate:*** Beclometasone dipropionate is the second largest type of MDI prescribed, representing 16% of all MDI sales. As shown in Table 4-2, the cost increment per inhaler varies depending on the dosage, the table doesn't show that additionally, many of the more expensive MDIs are breath-actuated. When taking the weighted average of price difference for each dosage, the price increment of using DPIs instead of non-breath-actuated MDIs is £0.38.

***Abatement cost, beclometasone dipropionate:*** Emissions are around 50 kg $CO_2$ per 200-dose inhaler. This makes the marginal abatement cost £21 per tonne $CO_2$ saved. This should be considered as the worst-case cost of abatement. Allowing for more effective use of DPIs by patients, less product wastage at end-of-life and larger volumes sold it is estimated that the marginal abatement cost would be significantly lower.

***Price increment compound drugs:*** Compound drugs (e.g. salmeterol + fluticasone propionate or formoterol fumarate + beclometasone dipropionate) represent 19% of all MDI sales. As shown in Table **4-2**, there is no cost difference between MDIs and DPIs in this part of the market.

***Abatement cost, compound drugs:*** As costs are equal the marginal abatement cost for switching to DPIs is zero.

### 4.7.2 Using Low GWP MDIs

Low GWP MDIs are not currently available. They are under development and it is recognised that development costs will be very significant. Discussions with propellant and drug manufacturers indicate that the overall cost of developing 5 different drugs using a low GWP propellant such as HFC-152a could be in the region of £100 million to £200 million. These costs are for:

- The toxicity testing of a new propellant.
- The toxicity and efficacy testing of an existing drug combined with a new propellant.

These development costs are one-off costs that apply on a global basis. Propellant manufacturers and pharmaceutical companies will amortise their development costs across the global sales of their products. If a number of drug companies develop a low GWP MDI for salbutamol (the most likely product to initially be developed as it represents such a large proportion of MDI sales) they will make that product available globally. Hence the UK will only fund a proportion of the total development cost. The UK population is around 1% of the world population. However, the UK is a large consumer of MDIs so it is likely that the UK will fund a much larger proportion than 1% - the likely figure could be in the range of 5% to 10%.

It is not yet known whether the production cost of a low GWP MDI will be different to the current generation of MDIs. HFC-152a is no more expensive to produce that the current propellants, so it is reasonable to assume that once the development costs have been amortised the on-going price of an HFC-152a propelled MDI will be the same as current prices.

Assuming:

a) Development costs of £200 million
b) Equal on-going production costs for MDIs made with HFC-152a and HFC-134a
c) UK funds 10% of total global development cost
d) All salbutamol MDIs switch to HFC-152a in period 2023 to 2028
e) Annual sales of 33 million salbutamol MDIs in 2023, rising to 38 million in 2032
f) The development costs are amortised over the 10-year period 2023 to 2032 (the end of 5th carbon budget period)

then the marginal abatement cost is around £2 per tonne $CO_2$ saved.

The marginal abatement cost will be higher if any of these assumptions are incorrect. For example, if the market for MDIs falls in size (through greater use of DPIs) then the development costs need to be amortised over a smaller volume of products. A key assumption is that on-going production costs are equal – this cannot be tested until the new products come to market. A conservative estimate is that the cost of abatement could be in the range £10 to £20 per tonne $CO_2$ saved.

### 4.7.3 An overall strategy

As discussed in Section 4.5, it is likely that a dual strategy is required, with much more widespread use of DPIs and the introduction of low GWP MDIs. This maximises patient options in the future and may help minimise the total cost of abatement.

- For around 20% of the current market (compound drugs), a switch to DPIs has zero cost.
- For 61% of the current market (salbutamol) a switch to low GWP MDIs should have costs of <£20 per tonne $CO_2$ saved.
- For 16% of the current market (beclometasone dipropionate) a switch to DPIs should have a cost of the order £20 per tonne $CO_2$ saved.

### 4.7.4 Overcoming the Barriers to DPIs and Low GWP MDIs

Under the current EU F-Gas Regulation, MDIs are fully exempted from the HFC phase-down, so there is currently no regulatory pressure to force a change away from current generation MDIs. It is worth noting that for most other EU countries, MDI usage is much lower than in the UK, hence they will form a much smaller part of the total F-Gas emissions. This might mean that there could be less enthusiasm at EU level for changes to the regulatory regime.

For the UK, MDIs represent one of the best opportunities for reducing emissions beyond those that will be achieved with current regulations. The cost of abatement analysis indicates that a switch to DPIs and a switch to low GWP MDIs are at acceptable cost, compared to other ways of reducing UK GHG emissions.

Discussions with experts have revealed that most GPs have little or no awareness of the GHG emissions created by current generation MDIs. Many GPs were aware of the ozone issue and believe that prescribing “non-CFC MDIs” is good for the environment. Whilst this is true (as CFC MDIs damaged the ozone layer AND had ten times higher GHG emission) there is little awareness of:

a) The high GHG emissions.
b) The fact that the UK uses far less DPIs than most other EU countries.
c) The fact that DPIs are used proficiently by a greater proportion of patients.

The CCC may wish to consider post-Brexit UK legislation that will force a switch away from current generation MDIs. An alternative strategy will be engagement with the NHS and NICE to try and create a much higher level of awareness of the issues discussed in this report and to encourage a greater uptake of DPIs. The CCC also need to consider how low GWP MDIs can also be brought to market as these will help create a long term strategy where over 95% of current emissions can be eliminated.

# 5 Enhanced mitigation options for Gas Insulated Switchgear (GIS)

## 5.1 Background

Gas insulated switchgear is used in the transmission and distribution of electricity. A gas is used to insulate high voltage components including bus-bars and switching equipment (interrupters). Since the 1970s, the gas used for GIS applications has been $SF_6$ (sulphur hexafluoride). This molecule has excellent electrical properties at the extremely high voltages encountered in electricity transmission systems. This allows the use of compact and cost-effective switchgear. Other benefits of using $SF_6$ are that it also very safe; neither toxic nor flammable and does not have any carcinogenic, mutagenic or repro-toxic (CMR) characteristics (T&D Europe, 2018); and it can operate at very low temperatures (down to -40˚C).

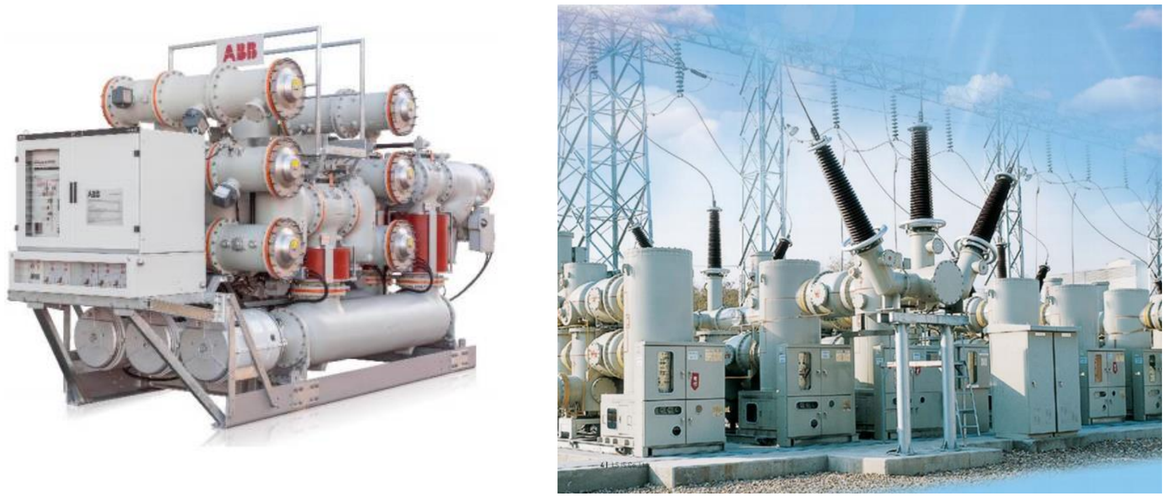
A key drawback in the use of $SF_6$ is that it is an extremely potent GHG. It has a global warming potential (GWP) of 22,800. It has the highest GWP of any of the gases regulated under the EU F-Gas Regulation[19]. **Table 5-1** illustrates GWPs of various gases for comparison. Life-Cycle Assessment performed on a gas-insulated substation shows that $SF_6$ emissions that can occur during the service life of the switchgear can represent between 60% and 80% of the total Global Warming impact of the substation over its whole life cycle (Laruelle *et al*, 2017).

**Table 5-1: GWPs[18] of Various Gases**

| Gas | GWP |
|---|---|
| $SF_6$ | 22,800 |
| HFC-404A | 3,922 |
| HFC-134a | 1,430 |
| $CO_2$ | 1 |

Because of its effectiveness as an insulating gas, $SF_6$ has been adopted globally by the electricity industry and it is widely used in the UK.

**Figure 5-1 Examples of gas insulated equipment**




### 5.1.1 Pre-$SF_6$ equipment

GIS using $SF_6$ was first introduced in the UK about 40 to 50 years ago. Prior to that high-pressure air insulated switchgear and oil filled switchgear were used. These are physically much larger than $SF_6$ devices and would be very expensive now. The best high-pressure air systems require 4 times as

[18] All GWPs in this report are 100-year values from the 4th Assessment Report of the IPCC. These are the values used in the 2014 EU F-Gas Regulation and in the current (2016) GHG inventory

[19] EU Regulation 517/2014 on fluorinated greenhouse gases

much equipment as $SF_6$. The UK transmission sector (mainly National Grid) still has some of these old designs of switchgear operating, but when they reach end-of-life they are replaced with $SF_6$ GIS.

### 5.1.2 GIS lifecycles

GIS equipment is usually used for very long periods. Indoor GIS can last 50 years and outdoor GIS 35 to 40 years. This means that the existing bank of $SF_6$ equipment will be in use for a considerable period of time until it is replaced.

### 5.1.3 Distinction between transmission and distribution

It is important to recognise the technology differences between GIS used in transmission and distribution:

- **Transmission** is the high voltage network that carries electricity over long distances from power stations to lower voltage local networks. Transmission takes place at voltages between 132 kV and 400 kV. GIS is used in various transmission applications. The transmission operators include National Grid, Scottish Hydro and SP Transmission.
- **Distribution** is the lower voltage network serving individual end users. Distribution is at voltages below 132 kV. Some GIS is used at 66 kV and most is at 33 kV and 11kV. The distribution network continues at lower voltages (mainly 3.3 kV and 415V) but these do not require $SF_6$ switchgear. Distribution is carried out by 14 licenced DNOs (distribution network operators) such as Northern Power Grid, Western Power and Electricity NorthWest.

The types of GIS required in transmission and distribution are different. It is easier to insulate switchgear at lower voltages. Distribution GIS tends to be small hermetically sealed units, with almost zero leakage. Transmission GIS units are much larger and have gasketed joints which do suffer from a small level of leakage.

### 5.1.4 Distinction between insulation and switching requirements

Some $SF_6$ is used simply for insulation of bus-bars and other high voltage lines. Some is used for switching (sometimes referred to as “interrupters”). When a switch is used (e.g. a domestic light switch at 240 V) a small spark is created when the metal contacts are close to each other. It is important to recognise that switching a high voltage cable is extremely demanding and very large and powerful electric arcs can be created. The role of simply insulating a high voltage line is much less “stressful” on the gas than a switching system.

### 5.1.5 Key suppliers

For transmission switchgear the main equipment suppliers are GE, ABB and Siemens. They all offer $SF_6$ equipment. They are all investigating alternatives as they realise that $SF_6$ will be under pressure in the future because of the high GWP. For distribution switchgear, Schneider is also an important supplier. Note, most of development work is being done at EU HQs of these companies, not in the UK.

### 5.1.6 Management of existing $SF_6$ assets

There have been significant improvements in gas management by transmission and distribution companies since the 2006 F-Gas Regulation (with some further enhancements following the 2014 Regulation). Historically $SF_6$ was simply vented to atmosphere during maintenance / at end-of-life. Now all gas is carefully recovered with specialised “recovery carts” (similar to RACHP refrigerant recovery machines) that compress and liquefy the $SF_6$ into a cylinder and clean out moisture / some other contaminants. Ofgem licences incentivise reduced $SF_6$ leakage. For transmission voltages, benchmark best practice leak rate is 0.5%. There have been steady improvements in leakage (expressed as annual leakage as % of installed bank) at National Grid during last 10 years (as shown in Table 5-2, based on emissions data in their environmental reports).

**Table 5-2 Bank size and emissions of $SF_6$ from National Grid**

| National Grid Data - published in their Annual Report | | | | | |
|---|---|---|---|---|---|
| | UK | | | | |
| | physical tonnes | | | Emissions | |
| | Emissions | Bank | Bank growth | kT CO2 AR 2 | % of Bank |
| 2007/8 | 13.8 | 453 | | 329 | 3.0% |
| 2008/9 | 10.8 | 470 | 17 | 257 | 2.3% |
| 2009/10 | 10.8 | 533 | 63 | 257 | 2.0% |
| 2010/11 | 13.7 | 612 | 79 | 326 | 2.2% |
| 2011/12 | 12.2 | 668 | 56 | 292 | 1.8% |
| 2012/13 | 11.8 | 700 | 32 | 282 | 1.7% |
| 2013/14 | 9.6 | 741 | 40 | 229 | 1.3% |
| 2014/15 | 9.1 | 792 | 52 | 217 | 1.1% |
| 2015/16 | 9.5 | 833 | 40 | 227 | 1.1% |
| 2016/17 | 11.8 | 731 | -102 | 282 | 1.6% |

The average emissions rate for the oldest $SF_6$ equipment is much higher than more modern equipment. National Grid's $SF_6$ bank has grown steadily as shown in inventory data. Growth is partly from the replacement of old non-$SF_6$ assets and partly from increasing grid size and complexity. The oldest $SF_6$ assets are beginning to reach end-of-life, which nominally is approximately 40 years.

## 5.2 Current UK Use and Emissions

UK emissions from GIS are estimated using environmental data published by the transmission and distribution companies on an annual basis.

In 2016 it was estimated that UK F-Gas emissions from GIS were 0.3 million tonnes $CO_2$ equivalent. This was around 2% of total UK F-Gas emissions in 2016.

2016 emissions were an estimated 13 tonnes of $SF_6$ from an equipment bank containing approximately 1,000 tonnes of $SF_6$. Hence the average leakage rate was 1.3%. It is estimated that 90% of the emissions are from the transmission networks and 10% from the distribution networks.

The rate of emissions has fallen considerably during the last 10 years. In 2007 emissions were 15.5 tonnes of $SF_6$ from an installed bank of 700 tonnes, i.e. an average leak rate of 2.2%. Since the 2006 EU F-Gas Regulations came into force, the use of $SF_6$ in GIS has been controlled. There are clear requirements to:

a) Take reasonable steps to avoid any leakage, including mandatory leak testing and repair.
b) Recover $SF_6$ from equipment during plant maintenance and at end-of-life.
c) Only use trained and certificated technicians to work on GIS containing $SF_6$.

These mandatory requirements, together with licence incentives set by Ofgem have led to improved containment and gas recovery.

## 5.3 Emissions Projections, 5$^{th}$ Carbon Budget Period

The current EU F-Gas Regulation has no controls over the use of $SF_6$ in new GIS. The existing controls, as described above, reduce operational and end-of-life $SF_6$ losses.

The bank of $SF_6$ in GIS has risen steadily during the last 10 years. However, bank growth is likely to stop and possibly reverse as older $SF_6$ equipment begins to require replacement and state-of-the-art $SF_6$ equipment is installed with much smaller $SF_6$ charge. Average leak rates can be expected to slowly improve as the old leaky $SF_6$ equipment is replaced with modern equipment which is more compact and has a lower level of leakage.

It is expected that without any change to the current Regulations GIS emissions will continue to fall slowly. Our estimates suggest that GIS emissions could fall to below 0.15 million tonnes $CO_2$ per year by 2030 if the transmission companies make on-going efforts to reduce leak rates and continue to replace end of life systems with the best available technology. The UK projections indicate that GIS will represent around 3% of UK F-Gas emissions during the 5$^{th}$ carbon budget period.

## 5.4 F-gas alternatives and improvements

### 5.4.1 Low GWP Alternatives

GIS equipment suppliers are investigating various alternatives to $SF_6$, recognising that the high GWP could be considered unacceptable in the long term. The two main options available are:

- Alternative gases to replace $SF_6$ in GIS.
- Alternative not-in-kind technologies to be used in place of GIS

The applicability of these different options depends on the size and voltage level of the current GIS application.

#### 5.4.1.1 Alternative Low GWP Gases

A number of alternative gases are being developed as alternatives to $SF_6$ in new GIS. The development work requires cooperation between a gas supplier and a GIS equipment manufacturer.

3M have proposed two alternative gases:

a) A fluoro-nitrile gas, Novec 4710
b) A fluoro-ketone gas, Novec 5110.

GE (who own Alstom) is developing new GIS based on a product they call $g^3$ (Green Gas for Grid). This is a mixture of Novec 4710 and $CO_2$. The mixture has a GWP around 200 which is around 1% of the GWP of $SF_6$.

ABB is developing new GIS based on Novec 5110, also used as a mixture with $CO_2$. This has the slight advantage of a lower GWP (below 10). However, it has the significant disadvantage that it cannot be used in sub-zero temperatures so can only be used in indoor / heated GIS.

One or both of these gases might be suitable for GIS at all voltages, but there is a lot of further development work required.

For distribution voltages other gases are being considered including an HFO and $CF_3I$.

#### 5.4.1.2 Not-in-Kind Technologies

$SF_6$ has the advantage of allowing compact GIS to be manufactured, saving space and cost. Other technologies can be considered; key options are air-insulated switchgear and vacuum interrupters.

Siemens are working on dry air and vacuum circuit breakers. This approach requires bigger equipment e.g. a 145 kV sub-station needs “170 kV sized equipment”. This could add 10% to 15% to costs.

At distribution voltages vacuum interrupters are already fully developed and are a realistic option. They are “industry standard” at 33 kV and available from most suppliers except Schneider. At transmission voltages they are likely to be much more expensive.

#### 5.4.1.3 Current Status of New Gas Technologies in the UK

National Grid have piloted the $g^3$ technology from GE. Sellindge, a new sub-station, was a pilot project. It was commissioned 12 months ago. It operates at 400 kV, but only the $g^3$ technology was only used to insulate busbars (line insulation), not for switching. $SF_6$ is still used at Sellindge for switching. National Grid have reported very good results from the first 12 months of this pilot.

It is important to note that National Grid do not consider the $g^3$ technology to be mature, especially for switching. Two new sub-stations are being built in the next year with $SF_6$ despite the success of the Sellindge pilot. National Grid need more commercial development of the new technologies before they could use outside of a carefully monitored pilot project.

The $g^3$ gas already can do switching at up to 145 kV and line insulation at 400 kV. National Grid commented that there are no technical barriers to using this gas for switching at 400 kV but that the equipment suppliers have a lot of development work to do before that is possible in the field. GE have sold around five 145 kV $SF_6$-free sub-stations using $g^3$ in Europe. Currently the Sellindge line insulation pilot is the only UK installation, although another is currently under consideration.

During discussions with National Grid it has been noted that approximately half of the $SF_6$ used is in Gas Insulated Lines (GIL) rather than switchgear although this can be very installation dependant. Based on this, and the success of $g^3$ the GIL pilot, the potential for replacing a large amount of $SF_6$ is already there, even if the new switch gear technology is not quite ready yet.

### 5.4.2 Improvements to new $SF_6$ Equipment

As older equipment begins to require replacement, new $SF_6$ equipment that is now installed are being developed to have a much lower "environmental impact" – including reductions in the charges of $SF_6$ used and reductions in $SF_6$ leakage rates. Laruelle *et al.* (2017) sets out various ways that GE are currently developing their new equipment to adhere to key environmental performance indicators. These include improvement of the seals used at interfaces; reduction of $SF_6$ quantity and the reduction in seal length. Further improvements have also been made in equipment assembly; this is now increasingly done in a factory rather than on site which reduces the risk of wrong assembly and leakages.

National Grid have plans to replace two $SF_6$ sub-stations this year. The new ones will be $SF_6$ but with only 20% of the $SF_6$ charge – the old $SF_6$ technology being replaced was very large (and relatively leaky). The latest $SF_6$ technology is much more compact has a much lower $SF_6$ charge and can achieve lower percentage leak rates. Old $SF_6$ designs required six interrupters – new designs only use one. As older $SF_6$ assets get replaced it is likely that bank growth will reverse as the old bulky equipment gets replaced.

The replacement of large sub-stations like these is a slow and expensive process. There is at least a two-year planning and building process, even after the design and technology of the sub-station has been agreed.

## 5.5 Projections

Because of the very long lifecycle of GIS equipment, the introduction of new low GWP gases will only have a small impact on emissions between now and 2032. In the short term, the most important action is minimisation of leakage from the existing bank, especially from the oldest and leakiest $SF_6$ equipment.

The technical potential for reduced emissions will be based upon the following options:

1) Ongoing: further efforts to reduce leakage from existing assets in both transmission and distribution networks.
2) Transmission: during next 5 years, replacement of old $SF_6$ GIS with state-of-the-art $SF_6$ equipment, with a lower charge and a lower leak rate.
3) Transmission: as soon as possible, replacement of old switchgear with low GWP gas technology or NIK technology. It is likely that this process will not begin until at least 2025, to give sufficient time for pilots to be completed and for product development to take place.
4) Distribution: possibility of earlier introduction of either low GWP gas technology or NIK technology when replacing old GIS. This could start by around 2022.
5) Distribution: as soon as possible, replacement of old GIL/busbars with low GWP gas technology or NIK technology.

With current Regulations we estimate 2032 emissions of below 0.2 million tonnes $CO_{2eq}$. With the introduction of low $SF_6$ of $SF_6$-free systems from around 2025 and significant investment to replace the current stock, this could fall to below 0.1 million tonnes $CO_{2eq}$ by 2032. Because of the long lifecycle of $SF_6$ GIS, it will take until around 2065 to approach zero emissions.

### 5.5.1 Modelled projections

Based on the above technical potential for reduction in emissions, and taking into consideration what might be possible, a model to estimate projected emissions has been produced. Scenarios in this model are currently only applied to National Grid emissions as these make up approximately 90% of the emissions in this sector and have the highest potential for reductions (larger, older, leakier equipment). The model outputs are shown for the following scenarios:

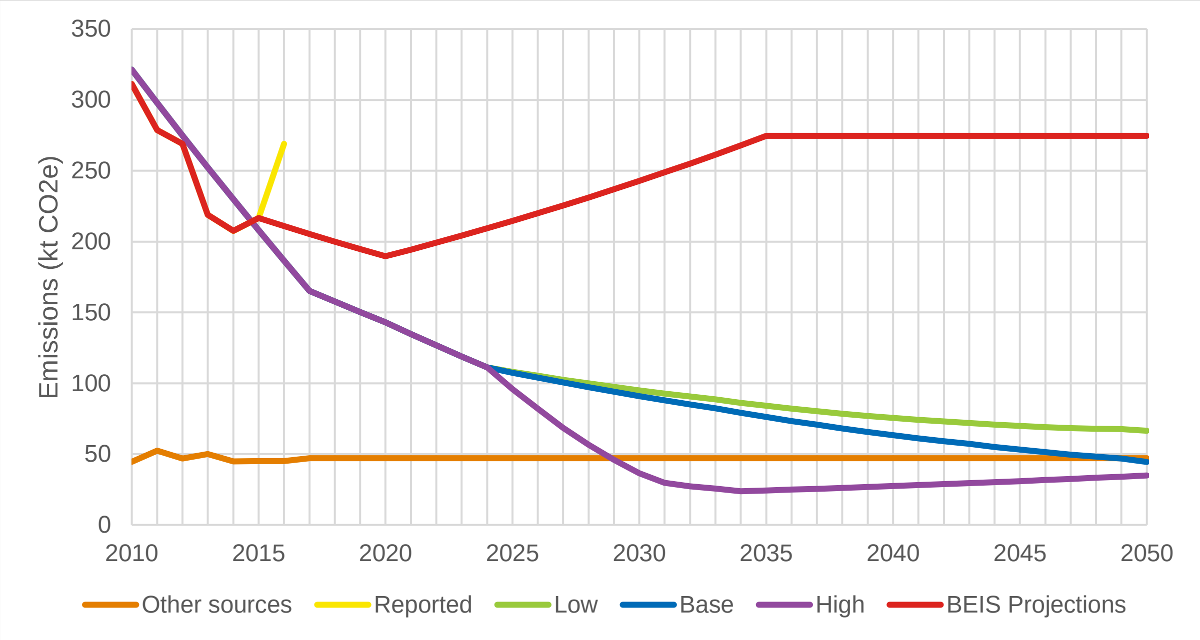
**Low**: No introduction of alternative technologies.
**Base**: Introduction of $g^3$ insulated lines from 2025 onwards. If $g^3$ or similar technology is accepted by the industry, we would expect the alternative technology to be used in new equipment. Note that there is currently no established alternative, so this scenario may not reflect real life outcomes.
**High**: Accelerated introduction of $g^3$ insulated lines from 2025 onwards at a factor of 4, leading to all pre-g3 tech being replaced by 2034. This is to illustrate the impact of an extreme measure to mitigate emissions from this source.

Note: all scenarios assume 2% growth per year in number of substations and upgrade of all substations at end of 40 year life time.

Other lines presented in Figure 5-2 are as follows:

**Reported**: Emissions reported by National Grid
**Other sources**: Emissions from distribution companies and those reported from power stations in the Pollution Inventory

**Figure 5-2 Projections to 2050 showing potential reductions in $SF_6$ emissions for the GIS sector**




### 5.5.2 Comparison with BEIS projections

The above plots include a comparison against BEIS emissions projections for National Grid emissions. Note, these projections have not yet been updated in 2018 so do not include emissions for 2016. Assumptions within the BEIS data are that the bank increases by 2.5% each year until 2035 and then are constant to 2050. National grid emission rate decreases by 5% each year until 2020 when it remains constant to 2050. To ensure consistency we have used a similar approach to increases in bank, however the BEIS emissions rate is a simplified version.

### 5.5.3 Assumptions within the model

This is a relatively simplistic model based on a few key assumptions.

One key assumption that has been used is the lifetime of equipment being 40 years. During discussions with industry experts and in reviewing documents, the figure of 35-40 years has been quoted. However, it is not clear whether this is a guideline, an estimate or a regulation. We suspect it is unlikely to be a regulation. If, for budgetary reasons it is decided to extend asset life, this could have a considerable effect on the projected emission.

## 5.6 Abatement Costs

The total costs of replacing all or part of the GIS and GIL equipment in the UK is difficult to quantify due to the size of the industry. However, most manufacturers as well as transmission and distribution operators are already "moving in the right direction". An indication of the difference in price between traditional $SF_6$ technology and low GWP alternatives can be given however.

Currently, non-$SF_6$ gases are more expensive than $SF_6$ – approximately four times more expensive. However, the price of gas is only a minimal factor in the overall cost of equipment. Non-$SF_6$ equipment is generally about 10-15% more expensive and additional space requirements where larger equipment is needed.

Our simple modelling suggest that the marginal abatement costs will lie in the approximate range of 380 – 3,000 £ per tonne of $CO_{2eq}$ abated

## 5.7 Conclusions

It is expected that without any change to the current Regulations GIS emissions will continue to fall slowly. As older equipment begins to require replacement, the new $SF_6$ filled equipment that is now installed are being developed to have a much lower environmental impact. Our view is that the alternative gas technology is not yet mature enough to be used across the UK grid. However, g[3] gas use in GIL has been piloted in the UK already with some success and some acceleration of implementation could occur.

The long lifetime of switch gear equipment and the relative immaturity of the non-$SF_6$ equipment means that accelerating complete replacement of all equipment would be difficult, very expensive, and not cost-effective. Replacement of large sub-stations like those which National Grid are replacing this year is a slow and expensive process. There is at least a two year planning and building process, even after the design and technology of the sub-station has been agreed.

# 6 Mitigation action costs relative to the no-policy scenario

The analysis of the previous chapters set out abatement costs relative to costs under existing policy. This short chapter considers the abatement costs relative to a “no-policy scenario”, in which the EU 2014 F-gas regulation is not being applied. The conclusion of this assessment is that the abatement costs are not significantly different between the two scenarios.

The difference between the scenarios are summarised in Table 6-1. The table presents a commentary on the abatement costs relative to the no policy scenario for RACHP, MDIs, and GIS/GILs. A more complete example of the logic to assess costs for Measure 1 in the RACHP sector is given in the table, and then, summary conclusions are provided for Measures 2 through to 6.

**Table 6-1 Mitigation action costs relative to the no-policy scenario**

| Sector | Measures | Impact on costs due to implementation of F-Gas regulations |
|---|---|---|
| **Refrigeration Air Conditioning and Heat Pumps**<br><br>(RACHP) | | |
| | • **Measure 1: Reduced use of R-410A in medium sized air-conditioning** | • The assessment of chapter 3 did not account for a difference in refrigerant price. The main additional cost of abatement was the redesign required to use low flammability refrigerants (compared to non-flammable refrigerants), which would mean an additional cost of ~£500-£1,500 to a typical ~£20,000 system.<br>• If the costs of the F-gases were included in addition to the equipment redesign costs, then the overall cost of switching from R-410A to HFC-32 would be slightly reduced in comparison to a no-policy scenario (as the lower GWP refrigerant, HFC-32, is slightly cheaper than R-410A at world market prices). Hence the cost of abatement would be slightly lower. |
| | • **Measure 2: Greater use of propane split air-conditioning** | • The assessment in chapter 3 did not account for refrigerant price.<br>• The difference in refrigerant prices between the current used versus the most likely new choice was minor compared to other costs and savings.<br>• The difference in these two refrigerant prices would have been even smaller before the EU F-gas quota. |
| | • **Measure 3: Reduced use of non-flammable HFO/HFC blends in small commercial, industrial and marine refrigeration** | • The assessment in chapter 3 did not account for refrigerant price.<br>• The difference in refrigerant prices between the current used versus the most likely new choice was minor compared to other costs and savings.<br>• The difference in these two refrigerant prices would have been even smaller before the EU F-gas quota. |
| | • **Measure 4: Retrofit of small R-404A equipment** | • In this case, a new drop in HFC is used to replace the existing R-404A.<br>• While our estimates of costs of retrofit would go up as we included the high cost of R-404A under the F-gas regulations, the estimated energy savings through the use of this gas are approximately an order of magnitude higher. These energy savings far outweigh the additional costs of retrofit. |

| Sector | Measures | Impact on costs due to implementation of F-Gas regulations |
|---|---|---|
| | • **Measure 5: Retrofit of R-134a equipment** | • It is expected that the technical methodology used to retrofit R-134a equipment will be similar to that used for R-404A retrofits described under Measure 4.<br>• The costs of abatement of this measure are already towards the higher end of the RACHP mitigation actions proposed.<br>• There is more uncertainty about the cost of these retrofits as they are not currently being conducted. |
| | • **Measure 6: Leak reductions through improved design and maintenance** | • The cost saving is likely to be higher under the no policy scenario. |
| **Metered Dose Inhalers**<br><br>(MDIs) | | |
| | • **Using DPIs** | • The current EU F-Gas Regulation exempts MDIs from the EU HFC phase-down, hence there are no direct regulatory pressures on this application of HFCs and no associated costs. Therefore the cost of abatement would be the same in a no policy scenario. |
| | • **Using Low GWP MDIs** | • The current EU F-Gas Regulation exempts MDIs from the EU HFC phase-down, hence there are no direct regulatory pressures on this application of HFCs and no associated costs. Therefore the cost of abatement would be the same in a no policy scenario. |
| **Gas Insulated Switchgear and Gas Insulated Lines**<br>(GIS / GILs) | | |
| | **All measures** | • The current EU F-Gas Regulation has no controls over the use of $SF_6$ in new GIS. The existing controls reduce operational and end-of-life $SF_6$ losses. The additional costs of these controls are minimal in relation to the operational and maintenance costs of GIS. Therefore the cost of abatement would be very similar in a no policy scenario. |

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# Appendix 1 - Consultations

## Expert Group

The following expert groups were identified and consulted:

**Refrigeration, air-conditioning, heat pumps:** Professor Graeme Maidment, London South Bank University; past-president of UK Institute of Refrigeration

**MDIs**: Professor Ashley Woodcock, University of Manchester; current co-chair of Montreal Protocol Technical and Economic Assessment Panel

**Gas insulated switchgear:** David Crawley, specialist consultant to Electricity Networks Association

**Generalists:** Davinder Lail, Alex Adamson and Anita Kanji, Stratospheric Ozone and Fluorinated Gases Team at Defra.

## Stakeholder consultation

| Company | Consultee |
|---|---|
| **F2 Chemicals** | **Bill Denison** |
| **Energy Networks Association (ENA)** | **Mark Dunk**<br>Head of Engineering |
| | |
| **ENA** | **David Spillett,**<br>Engineering Policy and Standards Manager |
| **ENA** | **Vincent Hay**<br>Engineer, Network Equipment |
| **ENA** | **Jane May**<br>Policy and European Affairs Officer |
| **EA Technology** | **Duncan Yellen** |
| **EA Technology** | **Jeff McCormac** |
| **Schneider Electric UK** | **Mike Adams**<br>Schneider Electric UK |
| **BEAMA Ltd** | **Anthony Bivens**<br>Technical Manager - BEAMA Networks and Flexible Energy Systems |
| **National Grid** | **Mark Waldron**<br>Switchgear Technical Leader<br>Engineering and Asset Management<br>Electricity Transmission Owner |
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