Department of Energy & Climate Change

Impacts of Leakage from Refrigerants in Heat Pumps

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The current UK heat pump market is relatively small in comparison to the dominance of gas boilers. This situation is, however, not compatible with the Government's carbon reduction targets. The Heat Strategy has identified heat pumps as a key technology to drive the decarbonisation of the heat sector in combination with the decarbonisation of the electricity grid. Driven by the Renewable Heat Incentive (RHI), the deployment of heat pumps is projected to grow significantly.

Refrigerants are a fundamental element of a heat pump installation as they are the working fluid which carries the energy from the heat source to the heat emitters. The most common fluids used in heat pumps are Hydrofluorocarbons (HFCs) which typically have a global warming potential over 1000 times that of CO_2. If the large scale deployment of heat pumps comes to fruition, the energy performance and displacement of existing fossil fuel heating technologies will have a significant impact on the ability of heat pumps to contribute to carbon reduction targets. As a result, the GHG emissions associated with refrigerant use will be increasingly important as deployment of heat pumps grows.

There is currently relatively little quantitative analysis available on leakage rates of refrigerants over the lifetime of a heat pump, yet the potential carbon benefits of heat pumps are likely to be very sensitive to leakage rates. The goal of this study was therefore to provide a more evidence based assessment of likely leakage rates for different heat pump installations over time. Driven primarily by the EU F-Gas Regulations, along with industry trends, it was also important to try to estimate the likely trends in refrigerant use, particularly with regard to Global Warming Potential (GWP).

At the same time, it is critical to present these impacts in the context of the benefits derived from heat pumps. The study therefore aims to model deployment of heat pumps and leakage of refrigerant according to a range of scenarios to present overall carbon dioxide equivalent (CO2e) net benefits or costs to both 2020 and 2050.

This report addresses the net benefit of heat pumps in the UK, taking into account the environmental costs associated with refrigerant leakage. The primary research and modelling indicated that whilst leakage led to significant CO2e emissions, this was nonetheless a small proportion of the total reduced emissions associated with heat pump technologies. It also highlights that there is scope to reduce leakage further, thereby increasing the net benefit associated with heat pumps.

The report focusses on the impact of air to water heat pumps (AWHPs), ground source heat pumps (GSHPs), and exhaust source heat pumps. The impact of a much larger number of existing air to air heat pumps (AAHPs) is also investigated. Due to uncertainties over this number, however, the report presents results both excluding and including AAHPs, which also demonstrates the different scale of impacts associated with the different technologies.

The key findings from the study can be summarised as follows:

1. It was determined from analysis of F-gas log books that annual leakage rates from operation of heat pumps were of the order of 3.8% of installation charge for non-domestic applications and 3.5% for domestic applications;
2. F-gas log books were used to determine leakage rates from heat pump operation, data was collected from 6 organisations which covered 528 unique installations. Analysis of this data suggest that 9% of non-domestic installations and 10% of domestic installations leaked each year;
3. Analysis of the F-gas log books indicated that when leaks occurred, the median proportion of refrigerant lost was 42% for non-domestic installations and 35% for domestic installations;
4. Analysis of the F-gas Log books also suggests very high proportions of charge loss associated with catastrophic leakage. For non-domestic applications, 75% of refrigerant loss is due to catastrophic leakage, whilst for domestic applications this rises to 92%. This suggests that the proportion of leakage associated with catastrophic failure is very high. As a result, this may represent an area for improvement in heat pump design to reduce the overall impact of leakage;
5. It was determined, however, that these log books were generally of poor quality, with many exhibiting the following characteristics:
    a. Refrigerant types not recorded;
    b. Type of installation was not recorded (i.e. heat pump / chiller etc.)
    c. Quantities of refrigerant added not recorded;
    d. Quantities of recovered refrigerant not recorded;
    e. The ID of the personnel performing the maintenance not recorded;
    f. Dates and results of leakage checks not recorded; and
    g. Cause and location of leak not recorded.

   This led to significant uncertainty within the modelling of this data. Whilst our assumptions and approach to data validation is set out in detail in this study, this suggests that there are significant challenges associated with using F-gas log books within the UK to provide a robust basis for analysis of this nature;
6. It is unlikely that further efforts to obtain good quality data from log-books would be successful as it is anticipated that the sample obtained during this research is broadly representative of the data held in the UK. Therefore to obtain more accurate data it would be necessary to either commission a long-term set of in-situ tests of leakage rates in operating heat pumps, or to enforce the maintenance of log-books in a manner that led to better record keeping, at which point the same data collection approach would lead to more accurate data;
7. The heat pump and refrigerant supply chains are complex. Data relating to these supply chain leakages also presented significant challenges, albeit the existing secondary data set was enhanced by a practical study to test the level of leakage from heat pump charging and recharging process, which showed that losses from this supply chain element are around just 0.062 kg per charge/recharge;
8. A further piece of practical research was undertaken to assess the impact of reduced levels of charge upon heat pump performance. These tests suggest that a refrigerant

charge reduction of 10% would lead to a relative coefficient of performance (COP) reduction of about 3% in heating and 15% in cooling operation respectively. Undercharging the heat pump by 40% would reduce the relative COP by around 45% in heating mode and 24% in cooling operation. For the heating mode in particular this is a very significant reduction in performance;

9. In discussion with DECC, and based on the Impact Assessments published to support the RHI, we modelled total heat pump deployment (under our central scenario) to reach around 430,000 installations by 2020 (excluding AAHPs) and 2,700,000 installations when AAHPs are included. This includes installations which are both supported and not supported by the RHI, along with those which would be eligible for support, but will not take this up. The vast majority (401,000) of the non-AAHPs are forecast to be in households, with only around 29,000 forecast in the non-domestic sector. The difference in levels of charge between these two sectors (3.3 kg for domestic and 24.5 for non-domestic), however, is such that the total levels of charge are likely to be of a similar magnitude by 2020;

10. The analysis shows that in non-AAHP installations over 2,000 tonnes of refrigerant, including over 1,200 tonnes of R410A (GWP 2088), will be in use in heat pumps in the UK in 2020. Notably, whilst the total number of heat pumps modelled during this period increases by almost ten-fold, the total refrigerant installed increases by only around half this amount. This reflects the increasing roll-out of domestic installations which have much lower installation charge;

11. Our modelling of leakage shows an increasing overall refrigerant loss by weight from 14 tonnes CO_2e in 2013 to 83 tonnes CO_2e in 2020 for installations excluding AAHPs. When AAHPs are included, this becomes 103 tonnes CO_2e in 2013 and 252 tonnes in 2020;

12. It was determined from the limited data available relating to the supply chain that the leakage from ongoing operation was the major contributor to refrigerant loss from such installations, contributing c.90% of quantifiable loss. This proportion declines moderately during the period but remains largely stable, indicating that the vast majority of the impact of refrigerants in heat pumps comes from the ongoing leakage, rather than losses associated with other life-cycle (or supply chain) stages. This indicates that a reduction in operational leakage rates would have the largest impact on refrigerant loss, despite the relatively high rate of loss due to end of life decommissioning. It is clear, therefore, that improvement of leak detection would have a significant impact on the overall loss of refrigerants from heat pumps;

13. The roll-out of heat pumps also provides benefits in terms of their replacement of existing fossil fuel heating technologies. As described in detail in Section 7.3, this benefit is determined by calculating the reduction in CO_2 emissions compared to these counterfactual technologies. The results of this analysis (excluding AAHPs) show that at 376,000 tonnes CO_2 per annum in 2013, rising to 2.19 million tonnes CO_2 per annum in 2020, the level of benefit is an order of magnitude greater than the emissions associated with refrigerant loss;

14. Our modelling shows that there will be significant growth in the total net CO_2e benefit from heat pumps (excluding AAHPs); from around 0.35 million tonnes in 2013 to 2.07 million tonnes in 2020. This is broadly equivalent to the total emissions from generating

electricity via one combined cycle gas turbine (CCGT) plant.[1] There is a similar pattern when AAHPs are included in the analysis, with net benefits of almost 6 million tonnes in 2020;

15. This analysis clearly suggests that the projected increased roll-out of heat pumps is beneficial in reducing CO_2e impacts through the displacement of more carbon intense technologies despite the associated rise in emissions due to refrigerant losses. If losses could be reduced through early leak detection this net benefit would grow further;

16. In the longer term, heat pump deployment was modelled to reach c.1.5 million installations under the central scenario by 2050/51, rising to over 4 million when AAHPs are included in the analysis. Due to the significant uncertainties associated with deployment after 2020/21, however, the low and high scenarios deviated from the central scenario by the order of 40%;

17. The number of heat pumps in operation will clearly drive the quantity of refrigerant being lost from heat pumps and so refrigerant loss is likely to be most sensitive to this variable. The results from our sensitivity analysis show that whilst the low scenario (excluding AAHPs) provides 18% less net benefit by 2020/21, the high scenario offers 45% more CO_2e saving over the same period. This indicates that the actual benefits will vary greatly according to the level of deployment, which suggests that the success of the RHI will be critical to delivering the potential CO2e savings associated with heat pump roll-out;

18. The leakage rates associated with heat pumps also have a direct impact on the total level of refrigerant lost. The results of the sensitivity analysis of this factor show that the sensitivity of the results to this variable over the period to 2020/21 is notable, but not as significant as that associated with variations in the levels of deployment modelled for this study. Under the high leakage scenario, associated emissions are 9% higher than the central scenario, whilst the low leakage scenario suggests a 13% reduction in emissions. It is therefore suggested that a reduction in leakage rates would have a notable effect on the net CO_2e benefits associated with heat pumps;

19. The modelling shows that over 6,000 (12,000 when AAHPs are included) tonnes of refrigerant would be installed in heat pumps by 2050/51 based on the projected deployment. The modelled leakage over this period increases to 278 tonnes per annum by 2050/51 from 83 tonnes in 2020/21, reflecting the increase in deployed refrigerant in heat pumps. When AAHPs are included in the analysis these figures rise to 532 tonnes in 2050/51 from 252 tonnes in 2020/21;

20. The negative impact associated with this lost refrigerant is calculated to be 46,000 tonnes CO_2e by 2050/51, compared to 128,000 tonnes CO2e in 2020/21 (excluding AAHPs). This significant reduction, despite the increasing loss of refrigerant, is due to the switch from HFCs to low Global Warming Potential (GWP) alternatives, such as ‘natural’ refrigerants and Hydrofluoro-olefins (HFOs). This significant shift from high GWP refrigerants to low GWP refrigerants over this thirty year period, is driven by the EU F-gas regulations;

[1] Based on a carbon intensity of 350kgCO2/MWh for a 1000MW output CCGT plant, which is operating for 5,000 hours per annum (which is reasonable given the current operating environment)

21. The analysis indicates that the maximum negative impact will occur in 20025/26, with 212,000 tonnes CO_2e attributed to refrigerant leakage (excluding AAHPs). It is clear, therefore, that switching to low GWP alternative refrigerants within heat pumps has a very significant impact in reducing emissions;
22. Similar results were noted when AAHPs are included in the analysis, with the negative impact from lost refrigerant calculated to be 89,000 tonnes CO_2e by 2050/51, compared to 430,000 tonnes CO_2e in 2020/21, with a peak in 2025/26 of 613,000 tonnes CO_2e;
23. In the longer term, the CO_2e benefits associated with heat pumps (i.e. from displacement of fossil fuelled heating systems) also increases markedly, with the 2020/21 figure of 2.2 million tonnes CO_2e per annum rising to 7.4 million tonnes CO_2e per annum by 2050/51. When AAHPs are included, the CO_2e benefits rise to 13.8 million tonnes in 2050/51 from 6.6 million tonnes in 2020/21;
24. The modelled net CO_2e benefit (i.e. the benefit from displacing fossil fuelled heating systems minus the amount of leakage) therefore also improves significantly over the period to 2050/51, growing from 2.07 million tonnes per annum in 2020/21 to 7.37 million tonnes per annum at the end of the period;[2]
25. The analysis shows that by 2050/51, the negative impacts associated with refrigerant leakage are projected to be just 0.62% of the calculated benefits, indicating the extent to which the deployment of heat pumps in the longer term will be beneficial in helping the UK meet its carbon reduction targets;
26. The analysis suggests that trying to reduce the level of leakage in the short-term whilst incentivising low GWP refrigerants in the longer term would be the most appropriate course of action to maximise the CO_2e benefits associated with heat pumps.

[2] When AAHPs are included in the analysis, the net benefit rises to 13.7 million tonnes in 2050/51

1.0 Introduction

The current UK heat pump market is currently relatively small in comparison to the dominance of gas boilers. This situation is, however, not compatible with the Government's carbon reduction targets. The Heat Strategy has identified heat pumps as a key technology to drive the decarbonisation of the heat sector in combination with the decarbonisation of the electricity grid. Driven by the Renewable Heat Incentive (RHI), the deployment of heat pumps is projected to grow significantly from 2020.

Refrigerants are a fundamental element of a heat pump installation as they are the working fluid which carries the energy from the heat source to the heat emitters. If the large scale deployment of heat pumps comes to fruition, the energy performance and displacement of existing fossil fuel heating technologies will have a significant impact on the ability of heat pumps to contribute to carbon reduction targets. As a result, the GHG emissions associated with refrigerant use will be increasingly important as deployment of heat pumps grows.

The report focusses on the impact of air to water heat pumps (AWHPs), ground source heat pumps (GSHPs), and exhaust source heat pumps. The impact of a much larger number of existing air to air heat pumps (AAHPs) is also investigated. Due to uncertainties over this number, however, the report presents results both excluding and including AAHPs, which also demonstrates the different scale of impacts associated with the different technologies.

1.1 Research Objectives

There is currently relatively little quantitative analysis available on leakage rates of refrigerants over the lifetime of a heat pump, yet the potential carbon benefits of heat pumps are likely to be very sensitive to leakage rates. The goal of this study is therefore to provide a more accurate assessment of likely leakage rates for different heat pump installations over time. Driven primarily by the EU F-Gas Regulations, along with industry trends, it is important to try to estimate the likely trends in refrigerant use, particularly with regard to Global Warming Potential (GWP).

At the same time, it is critical to present these impacts in the context of the benefits derived from heat pumps. The study therefore aims to model deployment and leakage according to a range of scenarios to present overall carbon dioxide equivalent (CO_2e) net benefits or costs to both 2020 and 2050.

1.2 Summary of Research Approach

The approach undertaken for this study includes a mix of primary research and practical testing exercises designed to provide the most accurate picture of refrigerant leakage and net CO2e benefits over time.

1.3 Report Structure

The report is structured as follows:

- Section 2.0 provides an overview of relevant policy and regulatory constraints relating to the use of refrigerants in heat pumps;

- Section 3.0 provides analysis of the current of UK policy mechanisms designed to drive heat pump deployment;
- Section 4.0 provides a review of the current refrigerants currently used in heat pumps and how this may change in future;
- Section 5.0 describes our approach to collection and analysis of data relating to refrigerant leakage from the operational phase of heat pumps;
- Section 6.0 describes our approach to collection and analysis of data relating to refrigerant leakage from the heat pump and refrigerant supply chains;
- Section 7.0 details the approach and results from some practical research undertaken for this study into the impact of reduced charge on heat pump performance;
- Section 8.0 details the assumptions used to model the environmental benefits and impacts of heat pump deployment;
- Section 9.0 presents the results from the core modelling exercise along with sensitivity analysis;
- Section 10.0 presents the key findings from the study.

2.0 Policy relating to use of Refrigerants in heat Pumps

Refrigerant policy in the UK is determined by the EU F-gas Regulations and EU Ozone Regulations.[3] [4] The existing F-gas Regulations were passed into EU law in 2006, and proposals for changes and additions to these regulations were made in 2012, with subsequent proposals published in 2014.[5] The current Ozone Regulations were passed into law in 2009. The current and proposed regulations for both areas of policy are discussed in Sections 2.1, 2.2 and 2.3, with particular reference to the heat pump industry.

2.1 Existing EU F-Gas Regulations

The existing EU F-Gas Regulations comprise a number of obligations which have all been passed in to UK law via the Fluorinated Greenhouse Gases Regulations 2009.[6] The information in Table 1, which summarises these obligations, shows that they largely relate to prevention and recording of leakage; certification of qualified personnel; and labelling. None of these obligations have specific impacts on the availability of HFCs for use in heat pumps. The only impact has been a financial and administrative burden on the owners, operators and service companies in the heat pump industry.

[3] European Parliament (2006) Regulation (EC) No 842/2006 of the European Parliament and of the Council of 17 May 2006 on Certain Fluorinated Greenhouse Gases, 17th May 2006, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:161:0001:0011:EN:PDF

[4] European Parliament (2009) Regulation (EC) No 1005/2009 of the European Parliament and of the Council of 16 September 2009 on Substances that Deplete the Ozone Layer, 16th September 2009, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:286:0001:0030:EN:PDF

[5] European Parliament (2014) *Proposal for a Regulation of the European Parliament and of the Council on fluorinated greenhouse gases*, 6th January 2014, http://www.europarl.europa.eu/meetdocs/2009_2014/documents/envi/dv/envi20140130_f-gases_agreed_v2_/envi20140130_f-gases_agreed_v2_en.pdf

[6] Great Britain (2009) *The Fluorinated Greenhouse Gases Regulations 2009,* 12th February 2009, *http://www.legislation.gov.uk/uksi/2009/261/pdfs/uksi_20090261_en.pdf*

No.	Obligation	Applicability to RAC Systems (using F-Gas Refrigerants)	Date from which Applicable in UK
1	Take steps to prevent F-gas leakage and repair detected leakage as soon as possible	All stationary systems	4th July 2007
2	Regularly Check for Leakage[7]	Stationary systems 3kg or more (or if hermetic and labelled 6kg or more)	4th July 2007
3	Fit automatic leak detection system	Stationary systems above 300kg	4th July 2007
4	Keep certain records about refrigeration plant that uses F-gases	Stationary systems 3kg or more	4th July 2007
5	Recover F gases during plant servicing and maintenance, and at end of plant life	All stationary systems	4th July 2007

[7] There are a variety of different checking frequencies determined by installation size, type (normal or hermetically sealed) and presence of automatic leak detection

No.	Obligation	Applicability to RAC Systems (using F-Gas Refrigerants)	Date from which Applicable in UK
6	• Use appropriately qualified personnel to carry out installation, servicing and maintenance, and leakage checking • Have company certification if employing personnel to undertake installation, maintenance or servicing of RAC systems • Further obligations for companies employing these personnel or wishing to take delivery of containers of F-gas	All stationary systems	4th July 2007
7	Label new equipment adjacent to service point/information and within instruction manuals	All stationary systems	1st April 2008
8	Placing on the market of non-refillable containers used to service equipment, except for those shown to have been manufactured in advance of July 2007	All systems	4th July 2007

Table 1: Obligations for operators under the Existing EU F Gas Regulation

2.2 Revised EU F-Gas Regulations

In contrast to the existing legislation, the revised EU F-gas Regulations (which are anticipated to be published in May or June 2014) contain a number of Articles which may have an impact on the heat pump industry through the control of F-gas availability.[8] Whilst it is highly unlikely that there will be further changes during Council approval and adoption, there still remains the possibility of alterations being made before publication in the official journal. Therefore this section should be read in conjunction with the published regulations once they have been officially published.

It is anticipated that the proposed Articles 13 and 14 will have the largest impact on the use of refrigerants in heat pumps in the UK. A large number of other proposed articles, however, have the potential to impact upon heat pump use and availability, as well as associated emissions. The analysis in Sections 2.2.1 to 2.2.7 addresses each Article that has any potential to change the dynamics of the UK heat pump market or to alter the refrigerant leakage rates from heat pumps.

In addition to this analysis it should be noted that the current definition of heat pumps in the proposed F-gas Regulations is different to the one included within the EU Energy Performance of Buildings Directive (EPBD).[9] This could potentially cause problems due to inconsistent legislation. Specifically this would mean that some installations would be classified as heat pumps under the EPBD but not under the Regulations, leading to a lack of clarity over which classification would apply for some installations. Whilst these regulations address different issues, it has the potential to cause confusion for operators.

2.2.1 Articles 3 & 4 – Checking for Leakage

The proposed regulations use different criteria for identifying the frequency of checks that need to be made on F-gas containing equipment than those used in the current version of the Regulations. The proposed change is from a simple weight-based measurement, to using total carbon dioxide (CO_2) equivalent global warming potential (GWP). This approach will lead to a leakage detection regime that will reflect the potential environmental impact of a leak (in GWP terms) of an installation. The proposed approach also has the potential to reduce the impact of leaks from small installations with high GWP as they will be detected earlier than under the previous approach. For example, a heat pump installation with a weight of between 3kg and 30kg must be checked at least annually for leakage under the current regulations. If this same installation has a GWP equivalent to c.50 tonnes of CO_2,[10] under the proposed revised Regulations this installation would need to be checked for leaks at least every 6 months. This increased frequency of check would, on average, identify leaks of high GWP installations

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[8] European Parliament (2014) *Proposal for a Regulation of the European Parliament and of the Council on fluorinated greenhouse gases*, 6th January 2014, http://www.europarl.europa.eu/meetdocs/2009_2014/documents/envi/dv/envi20140130_f-gases_agreed_v2_/envi20140130_f-gases_agreed_v2_en.pdf

[9] European Parliament (2010) *Directive 2010/31/EU of the European Parliament and of the Council of 19th May 2010 on the Energy Performance of Buildings*, 19th May 2010, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF

[10] For example, an installation rated for 25.0kW heating, 22.4kW cooling with 25 kg of R410a (GWP of 2088) will contain refrigerant equivalent to 52.2 tonnes of CO_2.

earlier than the current Regulations. This change is potentially important one that will affect leakage from heat pumps containing refrigerants.

Similarly, the requirement for automatic leakage detection would be transferred from refrigerant weight criteria to CO_2 equivalent (CO_2e) criteria. Under the existing regulations, any installation with 300 kg or more of refrigerant must have an automatic leak detection system fitted. The proposed Regulations require automatic leak detection for any installation with 500 tonnes CO_2 equivalent or greater GWP. Therefore, lower weight installations that do not require automatic leak detection under the current regulations but have a very high GWP, will be required to have automatic leak detection under the proposed changes.

The converse is also true, whereby installations with over 300kg of refrigerant but GWP of less than 500 tonnes CO_2e will no longer have to have automatic leak detection. The balance of these changes, however, in terms of direct emissions, will be to ensure all installations with very high GWP will have leak detection systems fitted, facilitating reduced leakage in CO_2e terms.

Conversely, it is also important to note that leakage from low GWP installations that goes undetected for longer due to the proposed changes in the F-gas Regulations, may have a negative impact beyond direct emissions. An installation that operates below design charge will require a larger energy input to deliver the same performance and thereby contribute to greater emissions depending on the energy mix used to power the installation. This issue is explored further in Section 7.0.

Whilst Defra is the responsible authority in the UK, enforcement of these aspects of the F-gas Regulations is currently the responsibility of the Environment Agency (EA) in England, in partnership with local authorities. The EA currently inspects sites that hold permits.[11] The EA also monitors and enforces compliance using a campaign approach, focusing on particular industry sectors and using risk-based targeting to check individual companies.

2.2.2 Article 5 – Record Keeping

The requirements for record keeping are proposed to be extended beyond those under the current Regulations.[12] There is an additional requirement to indicate where reclaimed and recycled refrigerant has been used to maintain an installation. This requirement is unlikely to have a significant impact on deployment of heat pumps and their performance. There is also a requirement for recording fluorinated greenhouse gases lost due to leakage. This will clearly indicate the loss of F-gas to the operators of such installations due to leakage. This may help highlight problems and lead to better maintenance of 'problem' equipment, which could result in reduced levels of leakage. This will also make data collection of leakage rates easier for any future studies into heat pump performance by government bodies or other institutions;

2.2.3 Article 8 – Training and Certification

This article addresses the requirements for training and certification of professionals working with F-gases across the EU. This does not contain any additional requirements that would

[12] See Section 5.2 for discussion of the current level of record keeping in the UK

potentially increase the costs of training; however, paragraph 7 retains the option for the Commission to utilise implementing acts in order to harmonise training. Therefore, whilst not currently the case, there is the technical possibility that requirements could be revised in the future. The current UK system fully reflects the existing obligations under Commission Regulations 303/2008 to 306/2008.

2.2.4 Article 9 – Restrictions

The influence on the heat pump sector of the original proposals on placing specific units and items on the market is likely to be limited to Item 11:

> "Refrigerators and freezers for commercial use (hermetically sealed systems)

The restriction is to be achieved by a two stage process as highlighted in Table 2, which shows the June 2013 amended requirements.

Unit Type	Date of Prohibition
Contain HFCs with GWP of 2,500 or more	1 January 2020
Contain HFCs with a GWP of 150 or more	1 January 2022

Table 2: Restrictions on Commercial Use Display Units

Whilst not extensively used for refrigerators and freezers applications, heat pumps containing HFCs are used for these applications in limited cases and the sector will therefore be impacted, if only in a lesser sense, by this proposed element of the Regulation.

Additionally, the agreed update published in January 2014 indicated a further two possible areas in which heat pumps could be affected. These are outlined in Table 3.

Placing on the Market Prohibitions	Date
11a. Stationary refrigeration equipment that contains, or that relies upon for its functioning HFCs with GWP of 2500 or more except equipment intended for application designed to cool products to temperatures below -50°C	1 January 2020
12a. Single split air-conditioning systems containing less than 3kg of fluorinated greenhouse gases, that contain, or that rely upon for their functioning, fluorinated greenhouse gases with GWP of 750 or more	1 January 2025

Table 3: Additional Article 9 Requirements which may affect Heat Pumps

Item 12a has the potential to impact upon heat pumps that are also primarily used for air conditioning. Often these will be in the form of Reversible Air to Air Heat Pumps (RAAHPs) that are operated in cooling mode only, or that are primarily operated in cooling but sometimes produce heating. Many of these systems have charges much less than 3kg and so would be affected by Article 9.

2.2.5 Article 10 – Labelling

The new requirements relating to labelling require the following (among a much broader set of updates):

- From 2017, the design quantity of greenhouse gases contained in the equipment, to be expressed in weight and CO_2 equivalent, must be indicated on the equipment;
- The above label information must also be included in user manuals; and
- For systems with CO_2e 150 or more, the information must be included in all marketing communications.

The above additional labelling requirements may make developers and installers more aware of heat pump units with higher CO_2e content. In terms of influence on the market, however, this will be just one factor among many in making a choice of technology and choices between different heat pumps, and therefore its overall impact is likely to be limited.

2.2.6 Article 11 – Control on use of F-Gases

The Article states:

> *The use of fluorinated greenhouse gases, with a global warming potential of 2,500 or more, to service or maintain refrigeration equipment with a charge size of 40 tonnes of CO2 equivalent or more, shall be prohibited from 1 January 2020.*

The important aspect of this article is the GWP figure of 2,500, which determines which refrigerants are affected by this restriction. Set at a level of 2,500, R404a is the only key refrigerant currently used in heat pumps which will be affected by this Article of the Regulation. R404a is used for very large scale installations and so its withdrawal will have an impact on a small number of non-domestic scale installations, but not on domestic and medium scale installations.

It should be noted that if this GWP figure were to be reduced in the future, this would bring other refrigerants into scope with lower GWP figures.

2.2.7 Articles 13 to 16 – Reduction in placing HFCs on the market

Article 13 addresses the availability of HFCs in EU Member States. It is proposed to limit the total amount that can be placed on the EU market from 2015. This will be achieved by allocating quantitative 'rights' (or quotas) to existing producers and importers to place HFCs on the market according to their existing market share, with a portion held back for new entrants. These rights will then be reduced every three years.

Years	Total Sales Permitted[1]
2015	100%
2016-17	93%
2018-20	63%

Years	Total Sales Permitted[1]
2021-23	45%
2024-26	31%
2027-29	24%
2030	21%

Notes:

1. The sales amount will be calculated by applying the percentages shown to the annual average of the total quantity produced and imported into the Union during the period from 2009 to 2012

Table 4: Proposed Reduction on HFCs in the EU

Quotas will be calculated using the data collected by the EC under the existing F-gas Regulations. These are intended to be based on sales data from 2009 to 2012, and will be calculated using a standardised methodology that takes into account refrigerant blends. It will also be possible for organisations that did not have any reported sales in the reporting period to propose an expected sales volume so that they can receive a quota. Subsequent recalculations of reference values for producers and importers will be conducted every three years (the first by 31st October 2017) to reflect changes in the market, with additional opportunities for new entrants to receive a quota. For the 2017 recalculations, these will be based on the annual average quantities of HFCs lawfully placed on the market after 1st January 2015.

The quota system will be administered using an electronic system, which will be developed and maintained by the EC. It is intended that this system will be in operation by 1st January 2015. The system will allow transfer of quotas between registered parties if advance notice is received. Paragraph 1a of Article 15 states that the Commission can adopt implementing acts to enable the smooth functioning of the register. Whilst no fee is explicitly mentioned, an allocation fee was discussed as part of the negotiations and this paragraph may facilitate the adoption of such a fee at some point in the future.

The proposed overall reduction in HFCs presents a potential constraint to the UK heat pump industry with regard to its potential market penetration. The proposed reductions will be occurring at the same time as an anticipated roll-out of large numbers of new installations in the UK (as explored in detail in Section 8.0). It is reasonable to expect that the reduction in HFC availability will lead to accelerated development of alternatives. In particular, for domestic installations it is anticipated that hydrocarbon (HC) based units will be brought to market in the short-term as the technology is tried and tested. The only limitation has been that it is currently not economically viable to make these commercially available at domestic scale; however, a reduction in HFC availability leading to an increase in HFC cost will eventually make them viable and create demand for such installations.

Similarly, whilst the choice of refrigerant will be less clear in commercial and industrial applications, there exist a number of alternatives. Indeed many are currently available already (for example larger HC units, Ammonia and CO_2 among others) and the adoption of these technologies will largely be determined by price. Additionally for many commercial organisations another driver for adoption of new refrigerants (and therefore a driver for development of new technologies) is the need for certainty in costs over many years. The reduction in HFCs that can be placed on the market will lead to price fluctuations that cannot be determined at this stage, and for many commercial organisations this will pose an unnecessary risk. In order to minimise this risk, it is expected that many such organisations will seek alternative refrigerants for installations so that they are not exposed to uncertainty in the longer term.

Increased demand for heat pumps driven by incentive mechanisms (for example, the Renewable Heat Incentive, as discussed in Section 3.1), however, may be dampened by the impact on the price or availability of units, which may be brought about by the reduced availability of HFCs. The relative balance between the reduction in HFCs and the availability and suitability of alternatives, however, is currently unclear.

Despite the scope for new organisations to claim quotas, there is a risk of a significant limitation on growth of sales of heat pumps that contain HFCs. This is dependent on the manner in which the quota system is implemented. In particular, due to the reference period being *before* the anticipated acceleration in market growth, it is unclear as to how quotas will be distributed in a situation where one part of the refrigerant market – that which relates to heat pumps - is expanding rapidly whilst other areas are more stable. Due to this lack of clarity, the European Heat Pump Association (EHPA) has argued that, because heat pumps have the potential to be a net contributor to CO_2e reduction targets, the EC should include the ability to revise quotas upwards as well as downwards in order to account for such changes in market proportion.[13]

It is unclear, therefore, to what extent this quota system will impact the heat pump industry due to the lack of clarity over how it will be implemented. If it is implemented without any revisions, however, it is possible that the heat pump industry may be disproportionately affected by this aspect of the regulations. This limitation may have a number of effects:

- Increased cost of heat pump installations;
- Reduced availability of units;
- Development of alternative refrigerants with lower GWP;
- Adoption of alternative refrigerants with **lower** efficiencies, compromising the COP efficiency factor of heat pumps and thereby reducing their carbon saving credentials; or
- Adoption of alternative refrigerants with **higher** efficiencies, improving the COP efficiency factor of heat pumps and thereby improving their carbon saving credentials.

In respect of the development of alternatives to HFCs, it is clear that other technologies that utilise them will be under similar pressures to the heat pump sector. It is therefore anticipated that there will be significant resource invested by the more established sub-sectors of refrigeration industry from which the heat pump industry may benefit.

[13] EHPA (2013) *EHPA position on the revision of the F-Gas regulation,* 1st July 2013, http://www.ehpa.org/homepage/?eID=dam_frontend_push&docID=790

With regard to the impacts on refrigerant leakage from heat pumps, it is anticipated that this part of the legislation will reduce the CO_2e emissions from installations that are switched to alternative, lower GWP refrigerants.

2.3 EU Ozone Regulations

The majority of obligations under the current Ozone Regulations have been in force since the beginning of 2010 in the UK, having been brought into UK law in 2009, and relate to HCFCs. These are summarised in Table 5. The majority of these obligations are already in force. The only outstanding changes that are due to take place are the following:

- Up to the end of 2014 only recycled HCFCs may be used for plant maintenance; and
- From 2015 HCFCs may not be used for plant maintenance.

These obligations are part of the ongoing efforts to phase out HCFCs which were initiated in 1987 with the signing of the Montreal Protocol, and which have subsequently been in force since 1st January 1989.[14] The Montreal Protocol and subsequent amendments seek to reduce the production and consumption of ozone depleting substances in order to reduce their abundance in the atmosphere, and thereby protect the ozone Layer. As of 2009 it became the first treaty to achieve universal ratification.

With specific reference to heat pumps, the only HCFC that is utilised for such applications is R22. It is anticipated, therefore, that these obligations will have a negligible impact on the heat pump industry as relatively few installations now contain R22.

No.	Obligation	Applicability to RAC Systems (using F Gas Refrigerants)	Date Applicable From in UK
1a	Stop using virgin HCFC refrigerant for plant maintenance	All systems	31st December 2009
1b	Only use recycled or reclaimed HCFCs for plant maintenance	All systems	1st January 2010 – 31st December 2014
2	Stop using recycled and reclaimed HCFC refrigerant for plant maintenance	All systems	1st January 2015
3	Take steps to prevent HCFC leakage and repair detected leakage as soon as possible and at any event within 14 days	All stationary systems	1st January 2010

[14] UNEP (1987) The Montreal Protocol on Substances that Deplete the Ozone Layer, http://ozone.unep.org/new_site/en/Treaties/treaties_decisions-hb.php?sec_id=5

No.	Obligation	Applicability to RAC Systems (using F Gas Refrigerants)	Date Applicable From in UK
4	Regularly check for leakage[1]	Stationary systems 3kg or more (or if hermetic and labelled 6kg or more)	1st January 2010
5	Record Keeping[2]	All systems	1st January 2010
6	Label equipment to which recycled or reclaimed HCFCs have been added	All systems	1st January 2010
7	Recover ODS during plant servicing and maintenance and at end of plant life	All systems	1st January 2010
8	Use appropriately trained personnel to carry out servicing and maintenance, leakage checking and recovery	All systems	1st January 2010
9	Non-refillable containers shall not be used to transport HCFC refrigerant	All systems	1st January 2010

Notes:

1. **The leak checking requirements for stationary RAC systems now mirror those for F gases. The exception is there is no requirement to fit automatic leak detection on systems of 300 kg and over. For equipment where this is fitted there is no reduction in the leak checking frequency**

2. **There are a number of record keeping requirements which depend on the size of the system and whether recycled or reclaimed HCFC refrigerants have been added**

Table 5: Obligations for Operators under the EU Ozone Regulation Obligations

3.0 UK Policy Mechanisms Impacting upon Heat Pump Development

The policy mechanisms driving the installation of heat pumps in the UK relate to incentives for introducing the technology as a low-carbon option to deliver heating and cooling in both non-domestic and domestic settings. The key instruments that are influencing the take-up of heat pumps are the Renewable Heat Incentive (RHI) and the Green Deal, the analysis of which is provided in Sections 3.1 and 3.2.

3.1 Renewable Heat Incentive (RHI)

The Renewable Heat Incentive (RHI) is the world's first long-term financial support programme for renewable heat. The RHI pays participants of the scheme that generate and use renewable energy to heat their buildings.[15] By increasing the generation of heat from renewable energy sources (instead of fossil fuels), the RHI helps the UK reduce greenhouse gas emissions and meet targets for reducing the effects of climate change. In contrast to the Renewable Obligation (RO) and small-scale Feed-in Tariff (FiT), both which incentivise generation of electricity from renewable sources, the RHI is funded out of general taxation rather than via levies on consumer bills.

The scheme has been developed in two distinct areas: 'non-domestic' installations, which started in November 2011; and 'domestic' installations, due to start in spring 2014. Prior to spring 2014, renewable heat in domestic settings has been incentivised by the Renewable Heat Premium Payment (RHPP). The non-domestic RHI is a 20 year inflation-linked subsidy. The domestic payments will be made on a quarterly basis for seven years, however the tariffs have been set at a level that reflects the expected cost of renewable heat generation over 20 years.

The detail of the RHI is discussed in the following sections with reference to how it affects heat pumps. Its impact on refrigerants in heat pumps will be determined by how the mechanism incentivises roll-out of new installations, which is explored in our modelling of market penetration in Section 8.1.

3.1.1 Non-domestic RHI

The non-domestic RHI currently includes tariffs for ground source heat pumps, whilst DECC has also recently announced new tariffs for AWHPs, which were previously excluded from the scheme. The extent to which these technologies are eligible and the level of incentive they receive are outlined below. Air to air heat pumps are not currently eligible for the non-domestic RHI. DECC will be conducting further work and gathering more evidence on introducing new technologies to the scheme as part of the non-domestic RHI review process.

Eligibility and Accreditation of Heat Pump Installations for the RHI

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[15] Participants must generate heat from eligible sources and use it to heat their buildings to be eligible for the RHI

Support under the non-domestic RHI is available to installations that meet the following criteria:

1. The equipment must be installed in England, Scotland or Wales on or after 15 July 2009;
2. The equipment installed must be new and of a certain size or 'capacity';
3. The equipment and installer must have Microgeneration Certification Scheme (MCS) or equivalent certification (if available for the specific type of installation);
4. The equipment must use liquid or steam to deliver the heat;
5. The equipment must be used to heat a space or water - or for carrying out a process where the heat is used within a building;
6. The equipment can't be used to heat a single home (though a combination of homes sharing a heating installation might be eligible – e.g. a block of flats). Support for single homes will be available under the domestic scheme, as discussed in Section 3.1.2; and
7. A public grant cannot be used to buy or install the equipment.

As outlined in Regulation 8 of the RHI Legislation, for a heat pump to be eligible under the scheme it is required that: [16]

a) *It generates heat using naturally occurring energy stored in the form of heat from one of the following sources of energy;*

    i. *The ground, other than naturally occurring energy located and extracted from at least 500 metres below the surface of solid earth;*

    ii. *Surface water;*

b) *In the case of a heat pump with an installation capacity of 45kWth or less, regulation 13 applies;*[17]

c) *It has a coefficient of performance of at least 2.9.*

Ofgem is the responsible agency for accrediting applications to the scheme and provides quarterly reports outlining the number of accreditations by type of technology and payments made under the scheme.

Subsequent to the commencement of the scheme it became clear that there was lack of clarity over the quantity of heat used by a ground source heat pump (GSHP) that was naturally occurring when it was operated under certain conditions. To gain greater efficiencies and thus make the installations more commercially attractive, most proposed designs for GSHP installations include both heating and cooling modes of operation which also capture or recover heat from additional ineligible sources, including:

- Recovery of heat from air conditioning installations;
- Capture of heat emitted by, for example, refrigeration equipment; and
- Capture of heat generated by solar thermal heat from pipes installed under nearby black tarmac.

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[16] HM Government (2011) *The Renewable Heat Incentive Scheme Regulations 2011,* 27th November 2011, http://www.legislation.gov.uk/uksi/2011/2860/pdfs/uksi_20112860_en.pdf

[17] Regulation 13 requires that the heat pump for which accreditation is sought is certified under the MCS and its installer was certified under the MCS at the time of installation.

This captured heat is then injected back into the ground for storage and subsequent use. To identify the proportion of heat that is eligible for RHI payment, Ofgem has adopted a simple set of tariff multipliers. This approach was developed by Eunomia on behalf of Ofgem and subsequently published in a letter from Ofgem to industry in December 2012, thus allowing the accreditation of both pre-existing applications and new installations.[18] The multipliers are shown in Table 6. It is anticipated that these might be further refined in the future.

Installation Type	Percentage of Naturally Occurring Heat Eligible for RHI Support
Heating-only	100.0%
Small Non-heating-only (<100kWth)	72.3%
Large Non-heating-only (≥ 100kWth)	64.7%

Table 6: GSHP Tariff Multipliers for Heating and Cooling Configurations

DECC has also issued clarifications regarding which sources of heat are classified as eligible.[19] These are summarised in Table 7.

Heat Source	Eligibility
Solar collectors	**Fully compatible with RHI**, but only GSHP tariff (not solar thermal tariff) will be payable on that heat
Waste heat from space cooling and process cooling	**Compatible with RHI**, providing total heat produced by heat pump does not exceed five thirds of the heat drawn from the ground loop
Waste heat from industrial processes	**Compatible with RHI**, treated in the same manner as waste heat from cooling
Direct heat from CHP systems	**Not compatible with RHI** at present, due to concerns over interaction with CHPQA, but will consider further under 2014 Review
Heat from fossil fuel or renewable boilers	**Ineligible**, to avoid a situation where heat is generated only to be stored in the ground

Table 7: Clarifications for Heat Source Eligibility

Tariff Levels

[18] See http://www.gshp.org.uk/pdf/Eligible_heat_criteria_for_ground_source_heating_cooling_systems_Ofgem.pdf

[19] DECC (2013) *Non-Domestic Renewable Heat Incentive: Improving Support, Increasing Uptake,* *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/265854/Non-Domestic_Renewable_Heat_Incentive_-_Improving_Support_Increasing_Uptake_-_PUBLISHED.pdf*

Following the tariff level review (which was included as part of the wider recent consultation on the RHI) new tariffs have been proposed which are due to commence from spring 2014.[20] As shown in Table 8, alongside the existing tariff levels, these new proposals significantly increase payments for heat pumps whilst holding biomass boiler payments static for small and medium installations. These proposed increases have been based on additional evidence on the costs and performance of technologies, market intelligence and stakeholder opinion on the level that the tariff should be set. This increase (both in absolute terms and relative to biomass boilers) is likely to make heat pumps more attractive for organisations for which installation is technically feasible, and thereby increase the number of applications and accreditations under the RHI. Furthermore, as shown in Table 8 DECC has also recently published tariff levels for AWHPs.[21]

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[20] DECC (2013) *Tariffs and Technologies Affected by the 2013 Non Domestic Early Tariff Review,* *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/204449/Tariffs_and_technologies_affected_by_the_2013_Tariff_Review_3.pdf*

[21] DECC (2013) *Non-Domestic Renewable Heat Incentive: Improving Support, Increasing Uptake,* *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/265854/Non-Domestic_Renewable_Heat_Incentive_-_Improving_Support_Increasing_Uptake_-_PUBLISHED.pdf*

Technology/Tariff (p/kWh)		Initial Tariff	Proposed Revised / New Tariff	Eligibility
Ground Source Heat Pumps	Small (up to 100kW)	4.8	Tier 1: 8.7 Tier 2: 2.6	21st January 2013
	Large (100kW and above)	3.5		
Air to Water Heat Pumps		N/A	2.5	4th December 2013
Biomass Boilers	Small (up to 200kW)	Tier 1: 8.6 Tier 2: 2.2	Tier 1: 8.6 Tier 2: 2.2	No Change
	Medium (0.2 up to 1MW)	Tier 1: 5.0 Tier 2: 2.1	Tier 1: 5.0 Tier 2: 2.1	No Change
	Large (1MW and above)	1.0	2.0 (M&W)	21st January 2013

Table 8: RHI Tariff Levels for Non-Domestic Installations[22]

3.1.2 Proposals for Domestic RHI

On 12th July 2013 DECC announced proposals for domestic RHI tariffs, which are planned to commence in spring 2014 and will also be open to legacy applicants that have installed units since 15th July 2009.

The domestic RHI will operate along the same principals as the non-domestic RHI, with applicants needing to meet eligibility criteria before a regular payment is made in proportion to the quantity of heat generated. The eligibility criteria and proposed tariff levels are outlined below.

Eligibility and Accreditation of Heat Pump installations for the RHI

There are a number of eligibility criteria that will need to be met in order for a domestic heat pump installation to qualify for the domestic RHI. For detailed information about these criteria please see the domestic RHI policy statement, and the subsequent changes to non-domestic RHI regulations.[23] [24]

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[22] There are also tariffs for solar thermal, deep geothermal, CHP, biomethane injection, and biogas. These have not been included to retain clarity

[23] DECC (2013) *Domestic Renewable Heat Incentive*, July 2013, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/212089/Domestic_RHI_policy_statement.pdf

[24] See https://www.ofgem.gov.uk/environmental-programmes/non-domestic-renewable-heat-incentive-rhi/policy-and-regulations

Properties and groups

Under the scheme, only single domestic properties will be eligible. Installations that heat two or more domestic properties may be eligible under the non-domestic RHI. The scheme can be applied for by the following:

- Owner-occupiers;
- Private landlords;
- Registered Providers of Social Housing; and
- Self-builders.

The following cases will be ineligible for the domestic RHI:

- New build properties by developers (though in some instances they may be eligible for non-domestic RHI);[25]
- Local Authorities which use 'Arm's Length Management Organisations' as the application must come from the owner of the system; and
- For more than one space heating renewable system in a property (except for solar thermal combined with one of the three other technologies).

Technologies

The heat pump technologies will be eligible for RHI payments under the domestic scheme are:

1. Air to water heat pumps; and
2. Ground and water source heat pumps.

As with smaller installations in the non-domestic RHI, all installations and installers must be certified under the MCS (or equivalent) at the time of installation.

Metering

Most domestic installations will not be metered and thus heat output will be 'deemed', although in a number of instances metering will be required. Installations will require metering under the following circumstances:

1. Where a renewable heating system is installed alongside a fossil fuel space heating system (e.g. an oil boiler) or another renewable system;
2. Where a heating system combines a heat pump with a fossil fuel system like a gas boiler (i.e. a hybrid system);
3. Where there is a biomass heating system that is not designed to heat the whole property; or
4. Where a heating system is installed in a domestic property that is occupied for less than half the year (e.g. a second home).

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[25] It should be noted, however, that self-build properties will be eligible

In addition, selected installations will have DECC's own metering equipment fitted so that it can check the assumptions it made about fuel bill savings and levels of heat output. For applicants, this means that they need to agree as part of the application process to having metering equipment fitted if the installation is chosen as part of DECC's metering programme. To assist this process, all new installations in the domestic RHI will need to be 'meter- ready' where possible. More details about this element of the scheme can be found in the aforementioned domestic RHI policy document.[26]

Heat pump specific criteria

There are also a number of specific RHI eligibility issues related specifically to heat pumps:

- Only heat pumps that run on electricity will be eligible;
- The minimum Seasonal Performance Factor (SPF) for a heat pump to be deemed as 'renewable' under the EU Renewable Energy Directive is 2.5 and therefore any installation with an SPF less than 2.5 will not be eligible for RHI payments;[27] and
- Finally, where a heat pump is installed alongside another space heating system, the heat pump will need to be metered in order to determine the proportion of heat demand that is met by the heat pump.

Links to the Green Deal

The domestic RHI will also be linked to the Green Deal, with an energy efficiency requirement.[28] Under this requirement, to be eligible for RHI payments, householders need to undergo a Green Deal assessment in order to access the RHI and, if the assessment recommends loft and/or cavity wall insulation, then these measures need to be installed before the household is eligible for RHI payments. This applies to legacy applicants as well as new applications.

Tariff Levels

The proposed tariff levels for the domestic RHI are shown in Table 9. These are higher than those for non-domestic installations as it is proposed that these will be paid for each eligible kWh over the course of seven (rather than 20) years, on a quarterly basis. The tariffs have been set, however, at a level that reflects the expected cost of renewable heat generation over the 20 year lifetime of the installation.

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[26] DECC (2013) *The Renewable Heat Incentive – Domestic: Impact Assessment*, July 2013, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/211978/Domestic_RHI_Impact_Assessment.pdf

[27] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:062:0027:01:EN:HTML

[28] Ibid.

Technology	Proposed Tariff (p/kWh)
Ground Source Heat Pump	18.8
Air Source Heat Pumps (air to water only)	7.3
Biomass Boilers	12.2
Solar Thermal	19.2

Table 9: Proposed Tariff Levels for Domestic Installations[29]

RHI payments for heat pumps will only be made on the renewable portion of their heat output. This is the energy that comes from the ground, water or air, net of the electricity used to run the heat pump.

The amount of heat generated is calculated using a 'deeming' calculation that estimates the household's expected annual heat usage. Multiplying the deemed figure by the technology's tariff rate will determine the annual payments. The deeming calculation for heat pumps will be the estimated heat use of a property after the installation of the required energy efficiency measures. Where an applicant already has these installed, the figure will be taken from the Energy Performance Certificate (EPC) done as part of the Green Deal Assessment (GDA). This figure will then be combined with the heat pump's expected efficiency. This will be determined from the following calculation which utilises the Seasonal Performance Factor (SPF):

Eligible heat demand = Total heat demand[30] x (1 – 1/SPF)

For newly installed heat pumps the SPF will be estimated by the MCS installer. For legacy applicants, an SPF of 2.5 will be assumed but applicants can arrange a full assessment by an MCS installer to demonstrate a higher rating if they wish.

3.1.3 Renewable Heat Premium Payment

The Renewable Heat Premium Payment (RHPP) scheme is administered by the Energy Saving Trust (EST) and concluded on 31st March 2014. In May 2013, the RHPP voucher levels were increased for the remainder of the scheme's lifetime in order to further incentivise uptake of renewable heating technologies. The technologies that can be supported by the scheme are determined by the current heating arrangement in a household, and this, along with the current voucher values, are summarised in Table 10. Additionally, as for the domestic RHI, there is now a requirement to have a Green Deal assessment before accessing the scheme.

In the period phases 1 and 2 (including phase 2 extension) vouchers were issued for 2,841ground source, and 6,847 air source heat pumps.[31] [32]

[29] Installations in the domestic RHI have to be MCS certified, which at present limits all installation sizes to a maximum of 45kW

[30] From the Energy Performance Certificate

Technology	Voucher Value	Eligibility	
		Households with or who have recently removed mains gas	Households with liquid gas, solid fuel or electricity
Air-to-Water Heat Pump	£1,300	✘	✓
Biomass Boiler	£2,000	✘	✓
Ground or Water-source Heat Pump	£2,300	✘	✓
Solar Thermal Hot Water	£600	✓	✓

Table 10: RHPP Vouchers and Eligibility

3.2 Green Deal

The Green Deal for households went live at the beginning of 2013 and is therefore in the early stages of implementation. It is also planned by DECC to potentially introduce a Green Deal for businesses.

The Green Deal aims to improve the energy efficiency of UK households through:

- Green Deal assessments that enable households to identify energy efficiency measures for their building; and
- For those who require it, finance through Green Deal loans to fund the measures.

There are three distinct elements of the scheme, namely:

- The Green Deal Assessment (GDA);
- The cashback scheme; and
- The loan scheme.

The take-up of each of these elements is growing, and it is anticipated that this will continue.[33]

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[31] Energy Saving Trust (2012) *Renewable Heat Premium Payment Scheme: Statistics as at Phase 1 Closure,* 10th April 2012, http://www.energysavingtrust.org.uk/Publications2/Generating-energy/Renewable-Heat-Premium-Payment-Scheme-weekly-statistics

[32] Energy Saving Trust (2012) *Renewable Heat Premium Payment Scheme: Phase 2,* 18th February 2013, http://www.energysavingtrust.org.uk/Publications2/Generating-energy/RHPP-Phase-Two-web-stats

[33] DECC (2013) *Domestic Green Deal and Energy Company Obligation in Great Britain: Monthly Report*, 27th June 2013, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/209097/Statistical_Release_-_Green_Deal_and_Energy_Company_Obligation_in_Great_Britain_-_Mid-June_2013.pdf

3.2.1 Green Deal Assessments

Green Deal Assessments can be obtained for a property from a Green Deal assessor. The assessment may carry an associated cost, but in some instances this may be offset against the cost of any work undertaken under the scheme where the provider which carries out the work also provided the assessment.

The assessment will identify cost-effective measures that can be taken to improve the energy performance of the building. The types of measures that may be recommended include:

- Insulation – for example solid wall, cavity wall or loft insulation;
- Heating;
- Draught-proofing;
- Double glazing; and
- Renewable energy generation – (including heat pumps).

Once the GDA has been conducted, a household can decide whether they wish to install any of the measures that have been identified as beneficial in the assessment. The household can choose to finance these themselves if they wish (for example though an existing mortgage, a new loan, or from savings), or they can apply for a Green Deal Loan from an approved provider.

3.2.2 Green Deal Cash-back

For certain improvements there is an associated ‘cash-back’ that can be redeemed once the measure has been installed.

3.2.3 Green Deal Loans

The Green Deal loans will cover the cost of installing any measures identified in the GDA and are tied to the property where the installation is made. They are paid back through energy bills over the course of 10-25 years. The ‘golden rule’ of the scheme is that the loan repayments will never exceed the reduction in energy costs associated with the new device(s). Therefore the household will always be better off than if the measure(s) not been installed. The loans are designed so that they can be accessed by many more people than commercial unsecured loans, and will therefore enable more households to improve their energy efficiency.

4.0 Review of Refrigerants Used in Heat Pumps

4.1 Historic and Current Trends for Refrigerant Use

Prior to the advent of regulations that regulate the usage of refrigerants, such as those implemented as part of the Montreal Protocol, refrigerant use was primarily driven by price and technical considerations. Refrigerants were developed initially for their efficiency, their suitability, as well as ease of manufacture. This had led to a number of synthetic refrigerants dominating the market (in the form of Chlorofluorocarbons – CFCs, and Hydrochlorofluorocarbons - HCFCs), particularly from the 1930s onwards.

With the growing awareness of the Ozone Depletion Potential (ODP) of CFCs and HCFCs, and the subsequent signing of the Montreal Protocol, gradually the once dominant CFC and HCFC refrigerants have been phased out due to their large impact on the Ozone layer. This has led to the increasing use of Hydrofluorocarbons (HFCs) as replacement refrigerants in various applications. Use of CFCs and HCFCs was common in heat pumps prior to restrictions being imposed, due to their efficiency in a variety of operation modes. R12, R114, R500, R502 and R22 were all used, but have largely been replaced by HFCs and blends, particularly the HFC R134a, and the blends R407C and R410A. All these refrigerants have similar performance characteristics to the refrigerants they have replaced, but sometimes with minor reductions under some operating conditions. Nonetheless they have been widely adopted in recent years and are now the dominant refrigerants used in heat pumps.

However, as discussed in the EU F-gas summary, the Global Warming Potential (GWP) of HFCs is now a significant environmental concern, with one tonne of some HFCs having over a thousand times the impact of one tonne of CO_2. Therefore, it is highly likely that HFCs will be further controlled in the future. As a result of these impending limits on HFCs, there is currently development by the industry of further synthetic refrigerants, particular Hydrofluoro-olefins (HFOs), of which R1234yf, R1234ze and DR-2 are the most recent refrigerants to be identified as a potential replacement for HFCs.

4.1.1 Natural Refrigerants

Prior to the development of the range of specialist refrigerants available on the market today, a number of naturally occurring substances performed this role. Whilst the majority of these have proved to be inefficient or unsuitable for a variety of reasons, a few have proved to be effective refrigerants for certain applications. The following substances in particular are still utilised as refrigerants:

- Ammonia;
- Hydrocarbons; and
- Carbon Dioxide (CO_2).

All of the above natural refrigerants have no Ozone Depletion Potential and relatively low GWP. Additional to these relative benefits, due to the lack of Chlorine and Fluorine in these substances, they do not form strong acids which can often lead to installation failures.[34] Each refrigerant is considered in more detail below.

It should also be acknowledged that both air and water vapour (R718) have been tested and used to limited applications, albeit these have not been given further analysis in this study for the following reasons:

- Waste vapour is currently not utilised in commercially available heat pumps due to the nature of the cycles required to utilise it effectively; and
- Air is relatively inefficient and requires large components. Its main application could be within situations whereby low ambient temperatures can be used to deliver free cooling possibilities. Whilst some units are currently being considered by supermarkets, it has not yet been used commercially.

Ammonia

Ammonia is a widely utilised refrigerant due to the relative energy efficiency it usually brings to heat pump installations. It also facilitates a high discharge temperature, which makes it possible to generate hot water using these systems. Additionally leak detection is simple due to its distinct smell, which can be easily detected by humans. For larger installations, however, there are potential safety concerns due to its toxicity to human life beyond certain concentrations. It is also flammable beyond 15% volume. As a result of these safety issues, there are two requirements for larger scale (>5kg) installations which use ammonia:

- No parts of a plant containing ammonia can be in direct contact with the public - this requires indirect systems to be installed; and
- Methods must be in place to prevent the escape of significant amounts of ammonia in the case of a catastrophic failure – this requires housings to be built around such installations.

As a result of these safety issues it is unlikely that Ammonia will be used for systems which are readily accessible by non-trained personnel, for example in standard domestic systems or for offices etc. Additionally, Ammonia is highly corrosive to Copper, and therefore requires steel pipework, which is better suited for larger applications.

The applications it may therefore be used in include larger commercial systems where the plant could be easily isolated, and domestic heat network schemes where the plant can be kept separate from residents. Ammonia-based heat network schemes have been installed in Norway by a UK company (Star Refrigeration), indicating that the technology is already available. Therefore as the drive to explore district heating in the UK develops, Ammonia heat pumps may become more common.[35]

[34] Bolaji, B., and Huan, Z. (2013) Ozone Depletion and Global Warming: Case for the Use of Natural Refrigerant - a Review, *Renewable and Sustainable Energy Reviews*, Vol.18, pp.49–54

[35] Buro Happold (2013) *London's Zero Carbon Energy Resource: Secondary Heat,* Report for Mayor of London, http://www.star-ref.co.uk/star/images/stories/pdf/gla_future_heat_report.pdf

Hydrocarbons (HCs)

Whilst often referred to as a single refrigerant, hydrocarbons come in the form of a number of different substances including propane, pentane, and butane which are all derived from oil. These substances exhibit good energy efficiency when utilised as refrigerants and are commonly used for a number of cycle systems. Whilst there are concerns over flammability, the specific mix of factors required to ignite HCs is such that they can be safely used in well-designed equipment. Due to this high level of flammability, however, hydrocarbon installations are restricted in the size of charge that can be used in specific applications when used as a direct cooling technology.

Carbon Dioxide (R744)

Unlike ammonia and hydrocarbons, CO_2 is neither toxic nor flammable. It is therefore often utilised where concerns around the safety of ammonia and hydrocarbons exist. Additionally CO_2 is a waste product from a number of industrial processes and so is widely available and inexpensive. The nature of CO_2 is that it requires a high pressure cycle. This poses a challenge, as it means that the cycle is less efficient than for a refrigerant that requires lower pressures. However, it also means that the discharge temperature is very high, typically 150°C, leading to better quality waste heat which can be very readily utilised for other purposes. It is of sufficient temperature that hot water can be readily generated to supply a water-based heating system, which is not possible with most refrigerant cycles.

As a result of the nature of the cycle, the use of CO_2 for heating-only or cooling-only applications is relatively inefficient. Where it is utilised to provide cooling, however, and the waste heat is also captured (i.e. it provides both heating and cooling simultaneously), there can be significant benefits due to the high temperature of the ‘waste’ heat. Consequently, CO_2 installations that produce both heating and cooling simultaneously are starting to gain traction in specific applications, in particular in supermarkets where there is a need to cool cabinets, but also to heat the shop floor at the same time. Supermarkets also utilise CO_2 as a refrigerant due to the certainty that it will be available (unlike HFCs etc.) and due to the low GWP of 1, which has a significant impact on their annual emission reports.

It is clear that where there are simultaneous cooling and heating demands, and where there is a desire for low CO_2e emissions, CO_2 is a very suitable refrigerant and as a result it may be utilised far more over coming years.

4.2 Potential Drivers for Future Change in Refrigerant Use

Cost and performance will continue to determine refrigerant choice, however the EU F-gas regulations and any subsequent updates are likely to be the most significant driver of refrigerant selection as through them some refrigerants are banned or made extremely expensive through limitations on sale. Those refrigerants that are not regulated under the F-gas regulations are likely to become more common. At this point in time this group includes the ‘natural’ refrigerants discussed above (i.e. primarily CO_2, hydrocarbons, and ammonia) and the new group of HFOs.

Table 11 shows the current selection of refrigerants used in heat pumps, along with potential new refrigerants that may become part of the market in the future. At this stage it is very difficult to identify the extent of future market penetration of each of these refrigerants, but as detailed in Section 8.2.2, we have undertaken this via a ‘profiled mix’ of these substances.

4.3 Summary Table of Heat Pump Refrigerants

	Refrigerant / Refrigerant Mix	Category	Thermo-Physical Properties[3]	Pressure & Density Regimes[5]	Chemical Stability	Environmental Impact			Safety Issues		Suitability to particular installations	Current point in development[2]	Replacement for[2]	Costs (£/kg)
						ODP[4]	GWP[1]	Acidifi-cation	Flamma-bility	Toxicity				
Existing	R22[6]	HFC	Boiling point: -40.8°C Critical temperature: 96,2°C Freezing point: -160°C	Critical pressure: 49.9 bar Vapour Pressure @21°C: 9.38 bar Vapour Pressure @55°C: 21.74 bar Vapour density: 3.0	The product is stable. Do not mix with oxygen or air above atmospheric pressure. Any source of high temperatures, such as lighted cigarettes, flames, hot spots or welding may yield toxic and/or corrosive decomposition products.	0.055	1810	At higher temperatures, (>250°C), decomposition products may include Hydrochloric Acid (HCI), Hydrofluoric Acid (HF) and carbonyl halides.	Non flammable	Non toxic Asphyxiation risk	Industrial Medium size Air-Conditioning	Fully Developed	N/A	No longer available due to EU Ozone regulation s
Existing	R407C	HFC	Boiling point:: 43°C Critical temperature: 86.2°C Freezing point: Not Determined	Critical pressure: 46.2 bar Vapour Pressure @21°C: 10.63 bar Vapour Pressure @55°C: 24.27 bar Vapour density: 3.0	Stable at ambient temperature and under normal conditions of use. Hazardous Reactions: May decompose on contact with hot surfaces and flames. Hazardous decomposition products: On contact with very hot surfaces, or flames, thermal decomposition (Pyrolysis) releases toxic gasses (hydrofluoric acid and possibly carbonyl halides).	0	1774	At higher temperatures (>250oC) decomposition products may include Hydrofluoric Acid (HF) and carbonyl halides	Non flammable	Non toxic Asphyxiation risk	Industrial Medium size Air-Conditioning	Fully Developed	N/A	14

	Refrigerant / Refrigerant Mix	Category	Thermo-Physical Properties[3]	Pressure & Density Regimes[5]	Chemical Stability	Environmental Impact: ODP[4]	Environmental Impact: GWP[1]	Environmental Impact: Acidification	Safety Issues: Flammability	Safety Issues: Toxicity	Suitability to particular installations	Current point in development[2]	Replacement for[2]	Costs (£/kg)
Existing	R134a	HFC	Boiling point: -26.2°C Critical temperature: 122°C Freezing point -92.5°C	Critical pressure: 40.6 bar Vapour Pressure @21°C: 5.91 bar Vapour Pressure @55°C: 14.71 bar Vapour density: 3.5	The product is stable. Do not mix with oxygen or air above atmospheric pressure. Any source of high temperatures, such as lighted cigarettes, flames, hot spots or welding may yield toxic and/or corrosive decomposition products.	0	1430	At higher temperatures, (>250°C), decomposition products may include Hydrofluoric Acid (HF) and carbonyl halides.	Non flammable	Asphyxiation risk	Small/medium/large Air-Conditioning Domestic fridges Car Air-Conditioning	Fully Developed	N/A	19
	R410a	HFC	Boiling point: -48.5°C Critical temperature: -72.8°C Freezing point: -155°C	Critical pressure: 48.6 bar Vapour Pressure @21°C: 14.84 bar Vapour Pressure @55°C: 33.80 bar Vapour density: 3.0	The product is stable. Do not mix with oxygen or air above atmospheric pressure. Any source of high temperature, such as lighted cigarettes, flames, hot spots or welding may yield toxic and/or corrosive decomposition products.	0	2088	At higher temperatures, (>250°C), decomposition products may include Hydrofluoric Acid (HF) and carbonyl halides.	Non flammable	Asphyxiation risk	Industrial Medium size Air-Conditioning	Fully Developed	N/A	20
	R404a	HFC	Boiling point: -47.8°C Critical temperature: 72.1°C Freezing point: Not Determined	Critical pressure: 37.4 bar Vapour Pressure @21°C: 12.61 bar Vapour Pressure @55°C: 25.57 bar Vapour density: 3.43	The product is stable. Do not mix with oxygen or air above atmospheric pressure. Any source of high temperature, such as lighted cigarettes, flames, hot spots or welding may yield toxic and/or corrosive decomposition products.	0	3922	At higher temperatures, (>250°C), decomposition products may include Hydrofluoric Acid (HF) and carbonyl halides.	Non flammable	Asphyxiation risk	Supermarkets Industrial	Fully Developed	N/A	18

	Refrigerant / Refrigerant Mix	Category	Thermo-Physical Properties[3]	Pressure & Density Regimes[5]	Chemical Stability	Environmental Impact			Safety Issues		Suitability to particular installations	Current point in development[2]	Replacement for[2]	Costs (£/kg)
						ODP[4]	GWP[1]	Acidification	Flammability	Toxicity				
Existing	R290 (Hydro-carbon)	HC	Boiling point: -42.1 °C Critical temperature: 96.7°C Freezing point: -185.89°C	Critical pressure: 42.5 bar Vapour Pressure @21°C: 7.51 bar Vapour density: 1.6	The product is stable	0	3		Flammable gas(when mixed with 20% air)	IDLH: 2100 ppm Chronic effects on humans: Causes damage to the following organs: the nervous system	Mainly domestic Some small size air-conditioning Supermarkets Industrial	Fully Developed	N/A	21
	R717 (Ammonia)	Ammonia	Boiling point: -33.34 °C Critical temperature: 132.4°C Freezing Point: -77.73 °C	Critical pressure: 114.24 bar Vapour density: 0.599	The product is stable under normal conditions.	0	0	Although ammonia is well known as a weak base, it can also act as an extremely weak acid	Flammable gas	Toxic – short term exposure limit is 35ppm	Mainly industrial Some medium size Air-Conditioning Supermarkets	Fully Developed	N/A	7
	R744 (CO_2)	CO_2	Boiling point: -78.5 °C Critical temperature: 31 °C Freezing Point: -56.6 °C	Critical pressure 73.77bar Vapour Pressure @21°C: 57.2 bar Vapour density: 1.52	The product is stable under normal conditions.	0	1		Non Flammable	In high concentration can be toxic and may cause asphyxiation.	Many application	Fully Developed	N/A	3
Potential	R32	HFC	Boiling Point: -51.7°C Critical temperature: 78.20 °C Freezing Point: -136 °C	Critical pressure: 53.8 bar Vapour Pressure @21°C: 10.32 bar Vapour density: 1.86	Stable under normal conditions.	0	675	Not yet published	Non Flammable	Not yet published	Not yet published	Not commercially available	R410A	N/A

	Refrigerant / Refrigerant Mix	Category	Thermo-Physical Properties[3]	Pressure & Density Regimes[5]	Chemical Stability	Environmental Impact			Safety Issues		Suitability to particular installations	Current point in development[2]	Replacement for[2]	Costs (£/kg)
						ODP[4]	GWP[1]	Acidification	Flammability	Toxicity				
Potential	R1234yf	HFO	Boiling point: -29.55°C Critical temperature: 97 °C Freezing point: -150°C	Critical pressure (bar): Ongoing Research Vapour Pressure @21°C: 6.83 bar[7] Vapour density: 5.98[7]	The product is stable under normal conditions.	0	4	Not yet published	Slightly flammable	Safe for use in its intended applications.	Automotive Air-Conditioning Supermarkets Medium Air-Conditioning Walk in coolers Residential chillers	Not commercially available until 2015 Lack of available components Not technically well proven	R134a	N/A
	R1234ze(E)	HFO	Boiling point: -19.0°C Critical temperature: 109.4 °C Freezing point: Not determined	Critical pressure (bar): 36.4bar	Current testing indicates the product is stable under normal conditions	0	6	Not yet published	Slightly flammable	Not yet published	Not yet published	Not yet commercially available	R134a	N/A
	R1234ze(Z)	HFO	Boiling point: 9.8°C Critical temperature: 150.1 °C Freezing point: Not determined	Critical pressure (bar): 35.3bar	Current testing indicates the product is stable under normal conditions	0	<10	Not yet published	Slightly flammable	Not yet published	Not yet published	Not yet commercially available	R245fa	N/A
	DR-2		Boiling point: 33.4°C Critical temperature: 171.3 °C Freezing point: Not determined	Critical pressure (bar): 29.03bar	Current testing indicates the product is stable under normal conditions	0	9.4	Not yet published	Non-flammable	Current testing indicates low toxicity	Not yet published	Not yet commercially available	HCFC 123 R245fa	N/A
	L-41	HFO	Not yet published	Not yet published	Not yet published	Not yet published Presumed 0	<500	Not yet published	Slightly Flammable	Not yet published	Not yet published	Not yet commercially available	R410A	N/A

Refrigerant / Refrigerant Mix	Category	Thermo-Physical Properties[3]	Pressure & Density Regimes[5]	Chemical Stability	Environmental Impact			Safety Issues		Suitability to particular installations	Current point in development[2]	Replacement for[2]	Costs (£/kg)
					ODP[4]	GWP[1]	Acidifi-cation	Flamma-bility	Toxicity				

1. CO_2 = 1. The GWP of R404a, R407C and R410A have been determined from the refrigerant composition percentage weight [BSI, 2008] and the GWP the different refrigerants composing these refrigerants over 100 years [IPCC, 2007]. For instance based on the British standard EN 378 [2008], the composition of R404a is R-125/143a/134a with respective percentage weight of 44/52/4. From IPCC [2007], the GWPs of R-125/143a/134a are respectively 3500/4470/1430. Therefore, the GWP of R404a is equal to ((3500x0.44)+(4470x0.52)+(1430x0.04))=3921.6.
   - Intergovernmental Panel on Climate Change (IPCC), 2007. IPCC Fourth Assessment Report (AR4). Climate Change 2007: Technical Summary. Contribution of Working Groups I, Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.
   - British Standards Institution (BSI), 2008. BS EN 378-1:2008: Refrigerating systems and heat pumps. Safety and environmental requirements. Basic requirements, definitions, classification and selection criteria. British Standard Institution, London, United Kingdom.
2. For potential refrigerants only
3. At atmospheric pressure
4. R11 = 1
5. Vapour density of air = 1.0 kg/m^3
6. The Ozone Regulation came into force in 2000 and it has already banned the use of ozone depleting HCFC refrigerants such as R22 in new installations. R22 remains a very common refrigerant in existing installations used by many air conditioning and process engineering users. The Regulation will ban the use of R22 as a “top-up” fluid for maintenance between 2010 (for virgin fluid) and 2015 (for recycled fluid).
7. Preliminary findings

Table 11: Comparative Table of Current and Potential Refrigerants

5.0 Collection and Analysis of Operational Leakage Data

There is very limited data which is publicly available on leakage rates from operational heat pumps. Consequently, a major data collection exercise was undertaken to source ‘log books’ to identify leakage rates from existing heat pump installations across the UK. The EU F-gas regulations require that log books are kept by owners and/or operators of heat pump installations containing refrigerants in excess of 3 kg. These log books are required to contain details of the leakage checks that have been carried out, any losses that have occurred and any associated action taken to rectify the problem if losses have occurred. It is therefore possible, in theory, to obtain an indication of leakage rates as log books should record the tests for leakage made at regular intervals, and the refrigerant lost between the previous test and the new test. This can then be converted into an annualised percentage of total charge lost.

The 3kg limit means that domestic scale installations are often excluded, although in practice a large number are recorded as they are maintained by organisations which also maintain larger installations and thus utilise standardised practices regardless of charge capacity. This is highlighted in the discussion in Section 5.2.

5.1 Methodology

Organisations that own or are responsible for maintaining heat pump installations in the UK were approached to obtain sets of log books. Whilst there was no obligation for any organisation to provide information, all organisations were assured that all data would remain fully confidential. 82 organisations currently operating in the UK were contacted and asked to provide F Gas log data to support the study. The nature of the organisations was diverse, reflecting the range of different types of organisations that work with heat pumps. The organisations included:

- Site owners;
- End users;
- Government departments;
- Consultants;
- Manufacturers;
- Distributors;
- Installers;
- Contractors;
- Trade associations;
- Technicians/ service engineers; and
- Training bodies.

Following an 8 week period allocated to obtaining log books, the whole sample was analysed to determine leakage rates, cause of leakage and location of leakage along with any other information that would inform understanding of the way heat pumps leak when in operation.

5.2 Results of Data Collection

Of the 82 organisations contacted, 46 (56%) indicated a willingness to participate in the study in the first instance. At the conclusion of the data gathering process, however, only 6 organisations (7%) actually provided data. This low capture rate is likely to have been influenced by:

- Concerns among stakeholder relating to the quality of the data available, as described in Section 5.2.1. Although such organisations had been assured that data would remain confidential, it seems that many perceived that there still remained a risk of adverse impacts; and
- Many organisations being willing to help, but unable to allocate time to identifying and obtaining log book data, particularly as the data collection period was during a very hot summer, during which many installations were requiring maintenance.

The data collected were from 6 organisations and covered 528 unique installations. These companies comprised:

- One heat pump manufacturer which produces a variety of different pumps;
- Two Heating Ventilation and Air Conditioning (HVAC) installers. These organisations install a wide variety of technologies and so heat pumps comprise only a limited proportion of their installations;
- One heat pump installer that specialises in heat pump technology;
- One HVAC maintenance company that maintains a wide variety of installations, including a number of heat pumps; and
- One end-user organisation that manages installations across a number of sites.

Of these 528 unique installations, 351 were from non-domestic scale heat pumps, and 177 were domestic installations by use. Also, of these 528 installations only 219 of these were in the standard F-Gas log book format. The remaining data were in summary form that was unique to the organisation in question. Where only summary information was provided, this did not cover all the information required by log books and so presented additional challenges, as discussed below.

Installations below 3kg

Whilst installations smaller than 3kg of refrigerant charge are currently exempt from the requirement to keep log books, a large number of the installations for which data were obtained had a charge size less than 3kg. The data collected for installations below 3kg was obtained from the same sources as for larger scale installations and therefore the assessment of log book quality in Section 5.2.1 applies to these installations. Nonetheless this data enables conclusions to be drawn about smaller scale installations in the context of the broader variety of installations.

5.2.1 Log Book Quality

Additional to the above challenges associated with the summary data, none of the log books received met the full standards required by the European Union's F-Gas Regulations, as described in Sections 2.1 and 2.2. Specific issues included:

- Refrigerant types not recorded;

- Type of installation was not recorded (i.e. heat pump / chiller etc.)
- Quantities of refrigerant added not recorded;
- Quantities of recovered refrigerant not recorded;
- The ID of the personnel performing the maintenance not recorded;
- Dates and results of leakage checks not recorded; and
- Cause and location of leak not recorded.

Furthermore, in many cases log books had only a single entry, indicating that a new log-book was started each time the installation was inspected. This meant it was not possible to identify the history of an installation, which has implications for identifying leakage rates.

All log books had at least one of the quality issues summarised above, and in most cases multiple data quality issues were identified. In order to work with the most reliable data, a quality appraisal of all the datasets was conducted including the summary data sheets (as although of a different nature, these exhibited similar data gaps to the log books), and a number of records were removed from subsequent analysis for the following reasons:

- No information about leakage or refrigerant added to the installation was included, which prevents assessment of quantity of refrigerant leaked;
- Only leak tests were recorded, not the subsequent action taken, which again prevents assessment of quantity of refrigerant leaked;
- Only ‘incidents’ were recorded, i.e. there was no data on installations which had not leaked, such that inclusion of this information this would ‘skew’ the results significantly; and
- Following checking against manufacturer data sheets to confirm the nature of the installation, some installations were revealed not to be heat pumps.

Following this process of exclusion or ‘vetting’, there still remained a significant data validation exercise and development of appropriate assumptions to enable analysis of much of the data, as described below.

5.2.2 Data Assumptions and Validation

The following assumptions were developed to enable the remaining data to be used for the purpose of calculating operational leakage rates:

- For the majority of data obtained in summary spreadsheet form, the companies providing it could not confirm whether the incidents for a particular unit were all recorded together. Therefore, in absence of any unique identifying number, it was assumed that each entry represented a unique installation. Therefore, where an explicit serial number was not listed, a sequence number was allocated and combined with the site name to provide a unique installation ID. This assumption may mean that in some cases multiple entries for specific heat pumps have not been identified. With no unique identifier provided, however, this was the only feasible approach to enable inclusion of the data;
- Where there was more than one set of data for a given installation in a single calendar year in the summary sheets or log books, the data were merged (and any refrigerant additions summed) to provide a single set of data for the installation for that year. This enabled all data to reported in an annualised format;
- No leakage reported:

  - Often log-book data indicated that a leak test had been performed but no leak found. In these instances it was assumed that the installation was leak-free, and that it had been leak-free for a 12 month period (i.e. 0% leakage over 12 months);
  - Similarly, where summary records stated nil refrigerant addition in a given calendar year, it was assumed this also indicated 0% leakage for that year.

  It should be acknowledged that this approach potentially results in an underestimate of leakage. This is because leakage tests (undertaken with hand-held devices) do not detect very small leaks or gradual leaks which have taken place historically. As a result, installations that indicate zero leakage during tests could in fact have been leaking; and
- Often log-books and summary data provided information for only one year. In these instances it was not clear over what period the refrigerant loss would have occurred. In these instances it was assumed that any leakage recorded occurred over the course of a single year. In some cases this may not be correct as a heat pump may not have been tested each year, and therefore the leakage could have occurred over a longer period of time (giving a lower leakage rate). In the absence of any data to the contrary, however, the assumption of leakage taking place over one year reflects the majority of log books where multiple year data was available.

The number and nature of the above assumptions indicate that there are uncertainties around the accuracy of some of the data. In particular, the last two issues could have a reasonable level of impact on the overall leakage results. It is not possible to quantify the extent to which these two issues may have affected the data, and therefore the subsequent analysis treats the overall derived leakage rates with caution and only makes use of the high-level, averaged findings from this data for analysis.

It is unlikely that further efforts to obtain good quality data from log-books would be successful as it is thought that the sample obtained during this research is broadly representative of the data held in the UK. Therefore to obtain more accurate data it would be necessary to either commission a long-term set of in-situ tests of leakage rates in operating heat pumps, or to enforce the maintenance of log-books in a manner that led to better record keeping, at which point the same data collection approach would lead to more accurate data.

Potential Need for a New System of Reporting Compliance

The quality issues regarding this data also raised questions about the nature of log book record keeping in the UK, as our sample indicated very low levels of compliance with the EU F-Gas regulations. It is anticipated that this level of compliance, whilst only taken from a relatively small sample, would be broadly reflective of the log books maintained in the UK as a whole.

As mentioned above, one particularly common issue was that many installation records contained only one entry. This implies either that log books are not being properly maintained or that the required testing under the F-Gas Regulations was not being performed. Either way, this lack of data quality represents a significant challenge to data collection activities regarding F-gas installations in the UK as, even if the log books can be obtained, the information therein is not likely to be of adequate quality to enable detailed analysis or strong conclusions to be made.

This situation is in stark contrast to that in some other EU Member States, for example Hungary which has instigated obligatory online reporting systems, which not only drive compliance with the F-Gas Regulations, but enable far easier collation of data. The online reporting system utilised in Hungary provides a simple form for reporting leakage information and therefore facilitates simple storage of this information in a database. This can then be readily accessed for analysis. It is also important to note that the German Environment Agency (Umweltbundesamt) also appears to be considering a similar approach.[36]

5.3 Assumed Leakage from Heat Pump Operation

Operational leakage was derived from analysis of the heat pump log books collected in the data collection exercise. As discussed in the Section 5.2, there are a number of uncertainties associated with this data, and therefore the results should always be considered or employed alongside the associated context.

Operational leakage rates were calculated by taking the total recharge quantity of an installation over the course of a year, and dividing this by the total charge of the installation, to give a rate in %. In a very few instances the refrigerant lost over the course of a year was greater than the total charge of the installation as there had been more than one major leak. In such instances the leakage rate derived was therefore greater than 100%. Catastrophic leakage is discussed in Section 5.3.2 of this report.

The vast majority of the leakage rate data points were a value of 0.0%, i.e. there was no leakage recorded, which heavily influences the dataset. In reality many of these 0.0% results could have included small leakages, but these would have been below the minimum detection level of standard, hand-held sensors. In the absence of any data to suggest otherwise, however, all such values have been assumed as 0.0%.

5.3.1 Deriving Leakage Rates from Log Book Data

In order to derive leakage rates from this dataset, it was necessary to split the analysis into two stages. The first focussed on the proportion of heat pumps that experienced a leak. This was achieved by taking the number of leakage incidents and dividing by the total number of records. This was calculated for non-domestic and domestic systems separately. The results were that 8.97% of non-domestic and 10.00% of domestic installations leaked in any given year.

The second step required assessing the median leakage rate and the 25th and 75th centile values for the systems that leaked, providing a central leakage with low and high scenarios. This approach yielded the values shown in Table 12. Such figures are much larger than those commonly quoted in the literature.[37] [38] This is due to the removal of all the systems that have not leaked from the dataset in order to allow a statistical analysis of the leakage data. With the

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[36] Umweltbundesamt (2011) *System for the collection, transmission and evaluation of data to identify specific and total F-Gas emissions from stationary refrigeration and air conditioning equipment and heat pumps in terms of Art. 3 of the Regulation (EG) No 842/2006*, October 2011
http://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/4181-0.pdf

[37] Schwarz, W., Gschrey, B., Leisewitz, A., et al. (2011) *Preparatory Study for a Review of Regulation (EC) No 842/2006 on Certain Fluorinated Greenhouse Gases*, Report for European Commission, September 2011, http://ec.europa.eu/clima/policies/f-gas/docs/2011_study_en.pdf

[38] Johnson, E. (2011) Air-Source Heat Pump Carbon Footprints: HFC Impacts and Comparison to Other Heat Sources, *Energy Policy*, Vol.39, pp.1369–1381

zero values retained within the dataset, the median value is zero and no meaningful centiles can be identified.

Having derived these leakage rates, it is possible to utilise the leakage frequency and leakage rate together to determine the equivalent annual rate for all installations of a particular type. This is achieved by multiplying the leakage rate by the frequency of leakage – so for the central non-domestic scenario, the leakage rate of 42% is multiplied by the leakage frequency of 8.97%. This gives an annual leakage rate for all non-domestic heat pumps of 3.77%, which is very similar to figures quoted in literature.

It is important to remember that these results are derived by assuming that all reported zero leakage figures do indeed represent installations that have not leaked. Given that many of these may have leaked somewhat, it is likely that the figures for leakage rates would reduce if such values were able to be included; however this would be offset by a similar increase in leakage frequency. Therefore it is anticipated that these figures are a good representation of the data collected.

Installation Type	Frequency of Leakage	Scenario	Leakage Rate for Systems that Leak	Equivalent Annual Leakage Rate[4]
Non-Domestic	8.97%	Low[1]	20%	1.81%
		Central[2]	42%	3.77%
		High[3]	85%	7.63%
Domestic	10.00%	Low[1]	18%	1.82%
		Central[2]	35%	3.48%
		High[3]	100%	10.00%

Notes:
1. 25th Centile Figure
2. Median Figure
3. 75th Centile Figure
4. Derived from the frequency of leakage multiplied by the leakage rate when leakage occurs.

Table 12: Operational Leakage Rates

The modelling of operational leakage employs the same split, assessing the number of pumps that leak in any given year, and then applying the leakage rates for those pumps only.

5.3.2 Assumed Level of Leakage from Major Failures

Having split the data between systems that do not leak, and those that do, it is useful to examine in greater depth the distribution of leakage rates to explore the frequency and severity of catastrophic failures.

For the purposes of this analysis, catastrophic failure is defined as greater than 50% charge loss, as this is the level of charge loss at which it is usual for most heat pumps to totally cease operating. Many manufacturers include (sometimes warranty) advice with their heat pumps that these will not operate following losses in excess of 40%. Our analysis in Section 7.0 demonstrates that some heat pumps do operate (albeit less efficiently) following such losses, and therefore we believe 50% lost charge is a more accurate (and 'conservative') assumption, of what would constitute catastrophic failure.

Taking the threshold as 50%, the results in Table 13 show the number of installations that failed catastrophically compared to all of those that failed (by leaking) to any degree. The information suggests that for both non-domestic and domestic heat pumps the proportion of catastrophic failures (46% and 50% respectively) is high in the context of all installations that leak to some degree. The result for non-domestic installations is slightly lower, which is likely to be the result of these often being maintained to a better standard. Nonetheless, however, this appears to indicate that a large proportion of leakage incidents result in a large proportion of refrigerant loss.

For some installations the failure mode may mean that the refrigerant lost as a result of these 'catastrophic' incidents may well occur close to instantaneously. In such incidents it is unlikely that any measures could be taken to prevent this leakage aside from improved design and construction of units and better maintenance. It is very likely, however, that some of these leakages will have occurred over a longer period of time. In such situations, automatic leak detection systems would potentially provide a means of identifying the leak and preventing further loss of refrigerant. Whilst the EU requires that automatic leak detection is fitted for installations of a certain charge size, it is also likely that significant losses could be prevented if automatic leak detection systems were fitted to smaller installations, albeit this may not be cost-effective at domestic scale.

The data within Table 13 should not be considered in isolation of the context in which it has been described. This is because, as discussed in detail above, it does not include the high proportion of installations for which 0.0% leakage was reported, when in reality, there may have been a small amount of refrigerant loss, which could not be detected by standard leak detectors. If many of these 'zero' reported leakages were indeed small leakages then this would significantly reduce the percentage of catastrophic failures.

Installation Type	No. of Catastrophic Failures	No. of All Instances of Leakage	Catastrophic Proportion
Non-Domestic	23	50	46%
Domestic	11	22	50%

Table 13: Proportion of Failures Identified as Catastrophic

Table 14 shows very high proportions of charge loss associated with catastrophic leakage. The figures of 75% and 92% (for non-domestic and domestic scale installations respectively) suggest that the proportion of leakage associated with catastrophic failure is very high. As a result, this may represent an area for improvements in heat pump design to reduce the overall impact of leakage.

Installation Type	Catastrophic Leakage (kg)	All Leakage (kg)	Catastrophic Proportion
Non-Domestic	244.45	326.37	75%
Domestic	38.83	42.43	92%

Table 14: Proportion of Charge Loss Due to Catastrophic Failure

5.3.3 Assumed Leakage Trends across Different Modes of Operation

Almost all of the heat pumps identified in the data collection exercise were defined within the log books and summary information provided by organisations which supplied data as operating both in heating and cooling modes. As a result it has not been possible to draw any conclusions relating to leakage from different operation modes from this dataset.

6.0 Collection and Analysis of Supply Chain Leakage Data

The supply chain for refrigerants in heat pumps includes the following processes that may result in leakage:

- Heat Pumps:
    - Manufacturing (outside UK);
    - Pre-charging small units;
    - Transportation to site; and
    - Decommissioning.
- Refrigerant:
    - Manufacturing (outside UK);
    - Delivery of refrigerant from manufacturer to distributor;
    - Delivery of refrigerant from distributor to site;
    - Charging / recharging during installation / repair / maintenance; and
    - Delivery of reclaimed refrigerant to suppliers.

Sections 6.1 and 6.2 describe the information available for each stage of the supply chain and, where information is largely absent, the steps that could be taken in order to obtain such information in the future.

It should be noted that identifying the leakage associated with each of these elements is challenging compared to operational leakage. Some are known to cause leakage and have been subject to investigation, for example manufacturing and decommissioning of heat pumps and manufacturing of refrigerant. In contrast there is very little published evidence regarding the leakage associated with various forms of transportation or leakage from evacuation and recharge of installations. Notably, therefore, for this study it was proposed to conduct the following two pieces of research to help inform knowledge of leakage rates from these elements of the supply chain:

1. Tracking of bottles through the supply chain within the UK in order to determine losses between both the distributor and site, and from reclaimed refrigerant returning to suppliers; and
2. A set of tests on a GSHP to identify the loss of charge associated with the evacuating and recharging process.

The approach to, and results from these specific elements of the study are described in Sections 6.2.3 and 6.2.4.

6.1 Heat Pump Supply Chain

The heat pump supply chain is relatively simple, with each unit being manufactured in a specialist factory before being distributed to site, where it usually will operate until end of life. At each stage of the supply chain, however, there are opportunities for leakage of refrigerant from the unit, or from processes associated with charging and emptying a unit. At this stage, the decommissioning of the pump presents the greatest potential leakage threat from the lifecycle aside from operation.

6.1.1 Manufacturing of Heat Pumps

Manufacturing of heat pumps currently occurs outside of the UK and so there is not a direct impact from the manufacturing process on refrigerant loss within the UK. Nonetheless, demand in the UK will have a direct influence on leakage of refrigerant in the country of manufacture. Refrigerant losses during manufacturing of heat pumps are largely related to where an installation is charged and evacuated, or when a small installation is pre-charged. The processes involved are well understood and the losses associated have been documented in academic studies.[39] These were examined, and the values utilised in the modelling (and their associated source) are summarised in Table 15. The studies identified indicated a relatively tight range of figures, with relatively minimal variation, giving good confidence in the range utilised in the modelling for this study.

Manufacturing Loss	Loss of Charge
Low[1]	1%
Central[2]	2%
High[3]	3%

Notes:

1. IPCC (2006) *IPCC Guidelines for National Greenhouse Gas Inventories. Volume 3: Industrial Processes and Product Use, Chapter 7: Emissions of Fluorinated Substitutes for Ozone Depleting Substances,* November 2006
2. IPCC (1996) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* September 1996
3. Greening, B., and Azapagic, A. (2012) Domestic Heat Pumps: Life Cycle Environmental Impacts and potential Implications for the UK, Energy, Vol.39, pp.205–217

Table 15: Manufacturing Losses

It is important to note, however, that the nature of measures to minimise leakage in manufacturing facilities will vary between countries and regions. As a result, heat pumps imported from regions with less stringent environmental controls may have caused greater leakage than academic studies report.

6.1.2 Transportation to Installation Site

Transportation of a heat pump may result in leakage if the unit is pre-charged, although there is currently a lack of evidence regarding the extent to which a heat pump will leak during this time. In order to determine the amount of leakage lost during these processes it would be necessary to examine three different aspects of transportation:

- The leakage from a unit from place of manufacture to freight container;
- The leakage of a unit whilst in transit in a container; and
- The leakage of a unit from been removed from freight container to place of installation.

The loss of refrigerant could potentially be identified by weighing a number of units at each step on the journey to identify any changes in mass, and thereby any loss of refrigerant (assuming

[39] Greening, B., and Azapagic, A. (2012) Domestic Heat Pumps: Life Cycle Environmental Impacts and potential Implications for the UK, *Energy*, Vol.39, pp.205–217

no loss of other elements of the heat pump. Alternatively this could be achieved by discharging the unit and determining the extra refrigerant needed to fully recharge the installation, taking into account the standard loss during such a process. In both instances it would be necessary to conduct such testing both in the country of manufacture and in the UK.

6.1.3 Decommissioning of Heat Pumps

Decommissioning of a heat pump can potentially lead to significant leakage depending on the process used. The potential losses from this stage are relatively well known compared to other elements of the supply chain, with a number of publicly available reports providing a range of data points.[40] [41] [42] [43] The range of data varies from c.9% loss to 55% loss, indicating a significant variation. This could be caused by a number of different factors, including:

- Type of installation;
- Level of care taken in decommissioning installation; and
- Charge capacity of installation.

The study by ICF International that aggregated a number of these studies recommended an approach of starting from a relatively high leakage rate (35% in 2010/11) and reducing over time to reflect improved practices (15% in 2030/31). In absence of primary data, it was determined that this was the best estimate available. To account for uncertainty regarding this form of leakage, however, a variation of 5% above the stated values and 5% below were utilised to determine low and high scenarios for use in sensitivity analysis. These leakage rates are shown in Table 16.

Period	Low	Central	High
2010/11	30%	35%	40%
2020/21	15%	20%	25%
2030/31	10%	15%	20%

Table 16: Decommissioning Losses

The relatively wide range of data points provided by these reports indicates the uncertainty of leakage rates during this stage of the lifecycle. All studies, however, indicate magnitudes of 10% or greater, which suggests that decommissioning of installations contributes significantly to total refrigerant loss.

[40] Schwarz, W., Gschrey, B., Leisewitz, A., et al. (2011) *Preparatory Study for a Review of Regulation (EC) No 842/2006 on Certain Fluorinated Greenhouse Gases*, Report for European Commission, September 2011, http://ec.europa.eu/clima/policies/f-gas/docs/2011_study_en.pdf

[41] IPCC (2006) 2006 *IPCC Guidelines for National Greenhouse Gas Inventories. Volume 3: Industrial Processes and Product Use, Chapter 7: Emissions of Fluorinated Substitutes for Ozone Depleting Substances,* November 2006

[42] ICF International (2011) *Development of the GHG Refrigeration and Air Conditioning Model: Final Report*, Report for DECC, December 2011

[43] Johnson, E. (2011) Air-Source Heat Pump Carbon Footprints: HFC Impacts and Comparison to Other Heat Sources, *Energy Policy*, Vol.39, pp.1369–1381

6.2 Refrigerant Supply Chain

The refrigerant supply chain is complex, as shown in detail in Figure 1. This complexity is a result of the wide variety of different organisations involved in the sector: Whilst a number of organisations provide more than one service, the relatively fragmented nature of the supply chain is such that there are often multiple routes that refrigerant 'bottles' can take from factory to installation and back again.

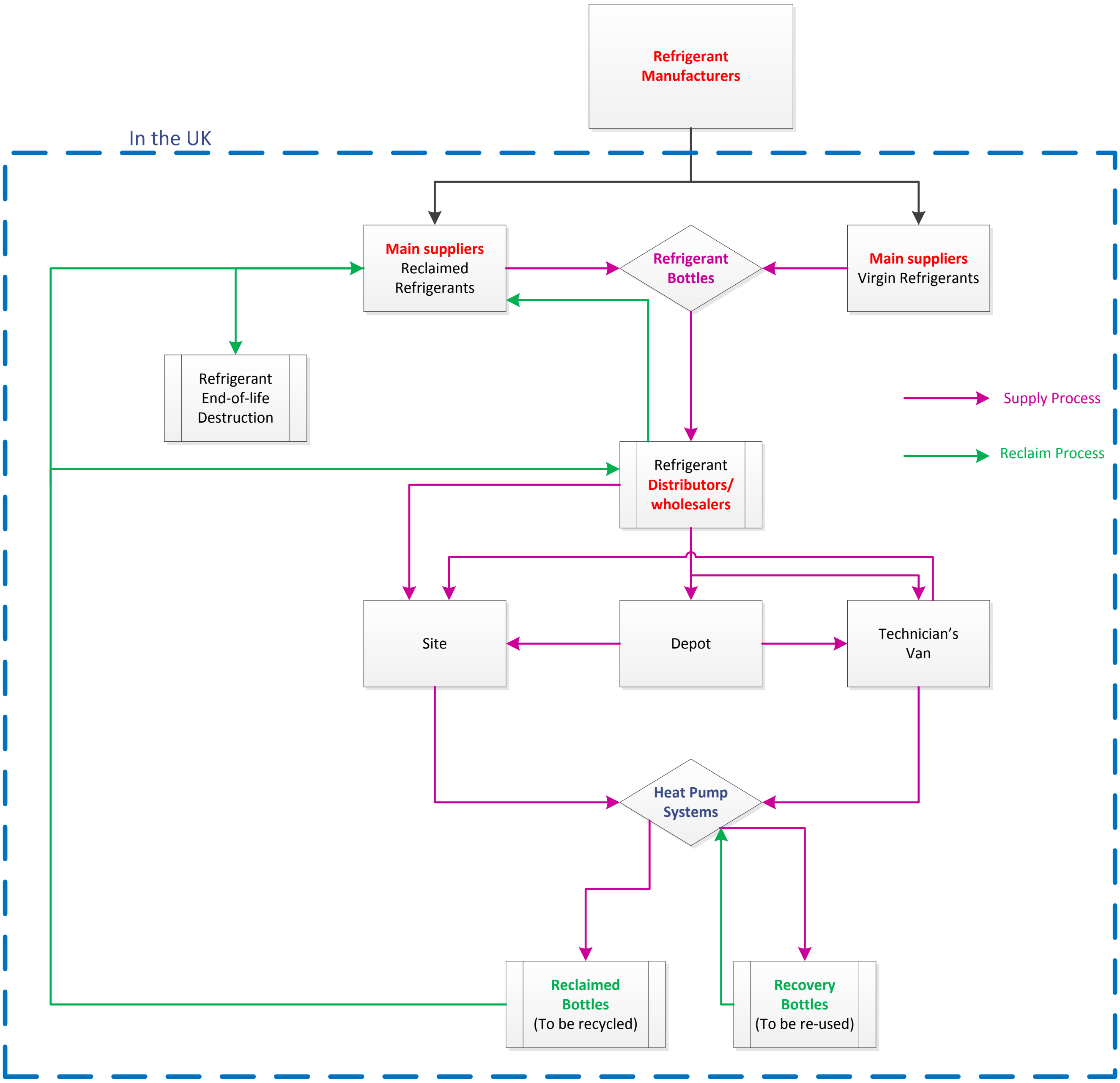

Figure 1: Schematic Representation of Refrigerant Supply Chain

6.2.1 Refrigerant Manufacture

Refrigerant manufacture varies dramatically depending on the refrigerant in question. Whilst the processes involved in producing HFCs and HFOs are complex but broadly similar, the production of natural refrigerants (CO_2, ammonia and hydrocarbons) is relatively simple, though with significant differences.

HFCs require a much larger set of input materials and processes for manufacture. Whilst detailed studies have been conducted into the broader environmental impact of the manufacture of HFCs, the actual release of HFCs during manufacture are not well documented. One lifecycle assessment (LCA) study quantifies the manufacture of one tonne of R134a as emitting 2.1 tonnes of CO_2e; albeit these emissions result from the whole manufacturing process, not solely refrigerant leakage, which would be somewhat lower.[44] Put in context, however, assuming a GWP of 1,430, this indicates that even if the entire CO_2 emissions were due to leakage, the leakage rate would be 0.14%. This indicates that the potential losses are relatively small. It is likely to be extremely difficult to test the losses associated with refrigerant manufacture due to the lack of a reference mass of refrigerant before the process starts. Therefore it is likely that this could only be conducted in very controlled conditions, which may well not be feasible.

Both ammonia and hydrocarbons are manufactured for a range of different uses and with far fewer input materials required. The potential leakage is, as with HFCs, therefore, very difficult to calculate and would require similarly challenging controlled tests to determine.

As CO_2 is produced as a by-product from a very large number of industrial processes, it is easy to obtain and indeed by capturing it for use as a refrigerant it is prevented from emitting to the atmosphere.

6.2.2 Refrigerant Supply to Distributor[45]

In the UK, there are three main refrigerant suppliers: Harp international; BOC; and A-Gas. These companies purchase refrigerants from manufacturers such as Dupont, Honeywell, Avanti Gas, Mexichem Flour, and from further suppliers in China. The refrigerants are stored in bulk storage tanks, which are refuelled by tankers, in tank farms (these are certified by the International Organisation for Standardisation - ISO). Different refrigerant types are stored in different tanks, which are mounted on load cells connected to a monitoring system that can display in real time the amount of product in each tank. The tanks are also fitted with alarms so any loss of product from a tank is automatically detected which instantly raises the alarm system that then alerts a remote, 24-hour manned monitoring centre. The tank filling process is semi-automated, in that an operative has to manually handle the cylinders, connect the filling hose, and initiate the cylinder-fill. The rest of the process is automatic.

All liquefied gas pressure cylinders and their valves are required to undergo a statutory ten year test. The test covers many parameters, including strength test, design test pressure test and corrosion-rust analysis. Assuming the cylinders and valves have passed the tests they can be used for the approved refrigerant. The valve assembly uses Polytetrafluoroethylene (PTFE) tape to seal the valve-cylinder threads. Not all refrigerants can be filled into any cylinder and suitability will depend on the required design pressure related to the refrigerant.[46] Refrigerants such as R410A will need a cylinder with a higher test pressure than say R134a (R134a can be

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[44] McCulloch, A., and Lindley, A. (2003) From Mine to Refrigeration: A Life Cycle Inventory Analysis of the Production of HFC-134a, *International Journal of Refrigeration*, Vol.26, pp.865–872

[45] It should be noted that the processes described in this section represent industry best practice, albeit they are widely followed and therefore are a fair reflection of how the industry operates

[46] The cylinder must have an appropriate Maximum Allowable Working Pressure and Test Pressure for the particular refrigerant

filled into a R410A approved cylinder but not vice versa). The cylinder's test pressure and permitted refrigerants are governed by the International carriage of Dangerous Goods by Road Regulation (ADR). This also details the maximum fill weights allowed for various refrigerants relative to the gross water capacity of the cylinder.

All cylinders are bar-coded, with the bar code detailing the individual cylinder number. This gives full traceability at all times for the cylinder and its contents (as well as cross-referencing the cylinder's test date status). When an operative connects a cylinder to be filled, providing the bar code is recognised and the cylinder is approved for filling, the system will first draw a vacuum on the cylinder. This has to be held for a pre-determined time period. If it is not held, filling is suspended and the cylinder removed from the filling line. If it is held, the filling commences. The cylinder, when being filled, is mounted on a trade approved/calibrated weighing platform which is connected to the automated filling system cut-off control system.

The filling line will feed liquid refrigerant into the cylinder and cut off when near the pre-determined fill weight, as entered into the control panel by the operative. The filling line will then gradually trim fill by adding incremental amounts until the correct fill weight is achieved. When this is done the operative will close the valve on the cylinder and press the control panel for the hose to release. The hose filling head has a draw-back pilot line in it to draw back any tiny amount of pressurised refrigerant gas that may have accumulated between the filling head and the cylinder valve. The filling process is totally non-emissive. There are leak detectors on the filling lines connected to a centrally processed alarm system that will sound if any gas whatsoever is detected. Once disconnected, a second leak check is made around the cylinder valve with a hand held electronic leak detector. If the cylinder passes this, the valve is shrink-wrapped with a polythene sleeve. The cylinder is then packed into a stillage with other cylinders and placed in the warehouse until sent out to distributor/customers.

The above description of the cylinder filling process demonstrates that there is minimal potential for leakage as the process is semi-automated and automatic leak detection is fitted to prevent any loss of refrigerant. Furthermore, once the cylinders are filled, they are shrink-wrapped to prevent leakage.

Despite there being clear controls on leakage during this process, there is no current understanding of the actual losses associated with this stage of the supply chain. In order to identify the leakage related to this stage it would be necessary to quantify:

- The leakage during tanker transportation (including transmission of refrigerant to and from the tanker);
- The leakage during bottle charging; and
- The leakage of a bottle from the depot to a distributor.

Leakage during tanker transportation would require comparing the quantification of refrigerant that was discharged at the supplying depot with the quantity recorded as having arrived at the supply depot. This is potentially feasible, but would require close liaison with all parties involved, in particular all the depots involved in one supply voyage.

It would also be possible to test the leakage of bottles once they leave the depot for the distributor by weighing the bottles at departure and arrival. This could be achieved with cooperation between the depot operator, the distributor and the organisation providing the transportation.

6.2.3 Refrigerant Supply post-Distributor

The loss of refrigerant between distributors and site is another area which is not well-documented, with no published data of leakage during this element of the supply chain. As discussed at the beginning of Section 8.3, it was proposed to undertake primary research using tracked bottles, whereby these would be weighed at each stage in their journey from the warehouse to site and on return (if relevant), along with records kept of the charges removed from them.

Following extensive negotiation with a number of distributors and contractors it was not possible within the scope and timeframe for this study to form the required set of agreements with an appropriate set of organisations willing to work together to track the same bottles through the full supply chain. This was primarily due to the effort required in order to accurately track these bottles and their weight at each stage of the process, and the extent of liaison between organisations that would be required. Such a study is possible, however, but to facilitate its success, both a greater timeframe for identifying willing parties, and a financial incentive to offset the costs of any associated impacts on logistics would be required.

6.2.4 Charging / Recharging a Heat Pump

The process of charging a unit, or reclaiming refrigerant and then recharging can lead to leakage, most notably from any refrigerant that remains in the line once the process is complete. As part of this study, a dedicated practical research project was conducted to identify a set of results for this element of the supply chain.

The research project utilised a cooling installation containing 1.2 kg of R404a. The installation was charged and discharged in the high side through a manifold charging apparatus. The charging and recovery process was conducted in accordance with Good Practice Guide 10 of IOR for Service Engineers.[47] Measurement of refrigerant loss during equipment charging and discharging (i.e. charging cycle) was carried out at London South Bank University. The measurement procedure included the following steps:

- Measuring initial mass of the refrigerant cylinder;
- Charging of the refrigerant into the refrigeration system;
- Measuring mass of the refrigerant cylinder after charge;
- Recovering refrigerant from the refrigeration system into the cylinder;
- Measuring final mass of the refrigerant cylinder; and
- Establishing the refrigerant loss in terms of mass.

The loss of refrigerant during the cycle was determined by identifying the difference between the starting and finishing point refrigerant cylinder mass. The procedure was repeated nine times and two different people carried out the measurements, alternating in order to account for

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[47] Institute of Refrigeration (2003) *Good Practice Guide: Charging Procedures (GPG 10)*¸ http://www.ior.org.uk/ZXEM5OEOAG

observer error. The results of this research are shown in Figure 2.

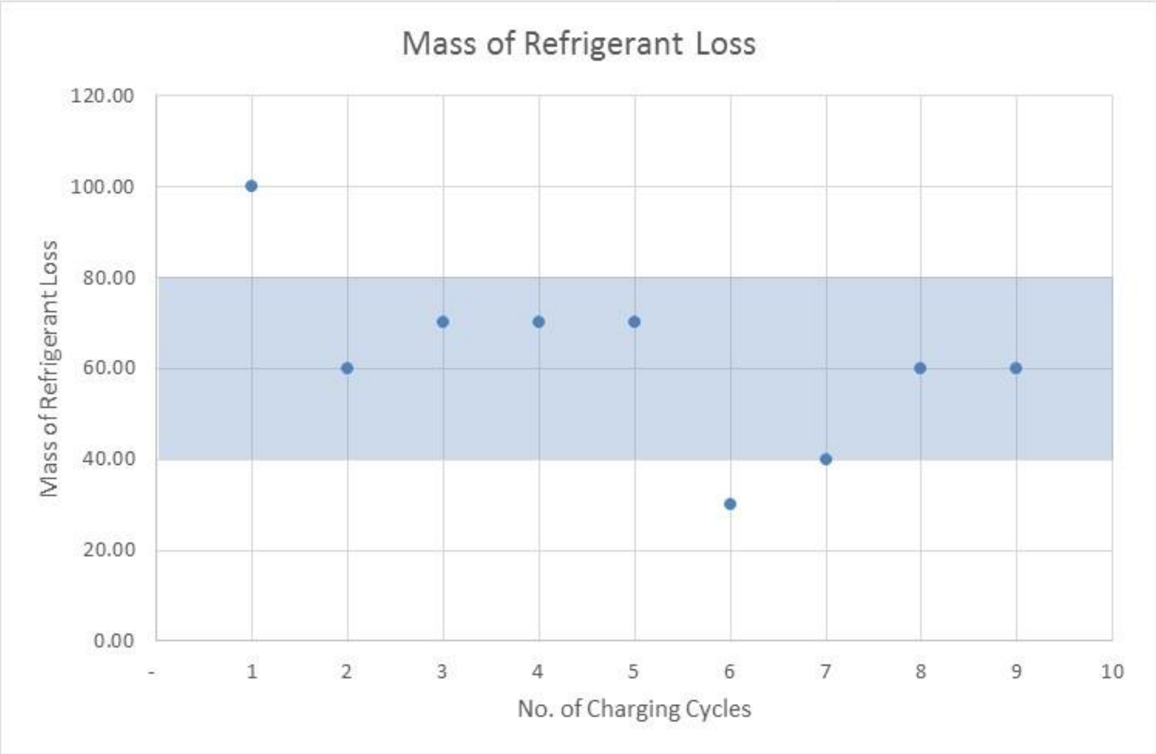

Figure 2

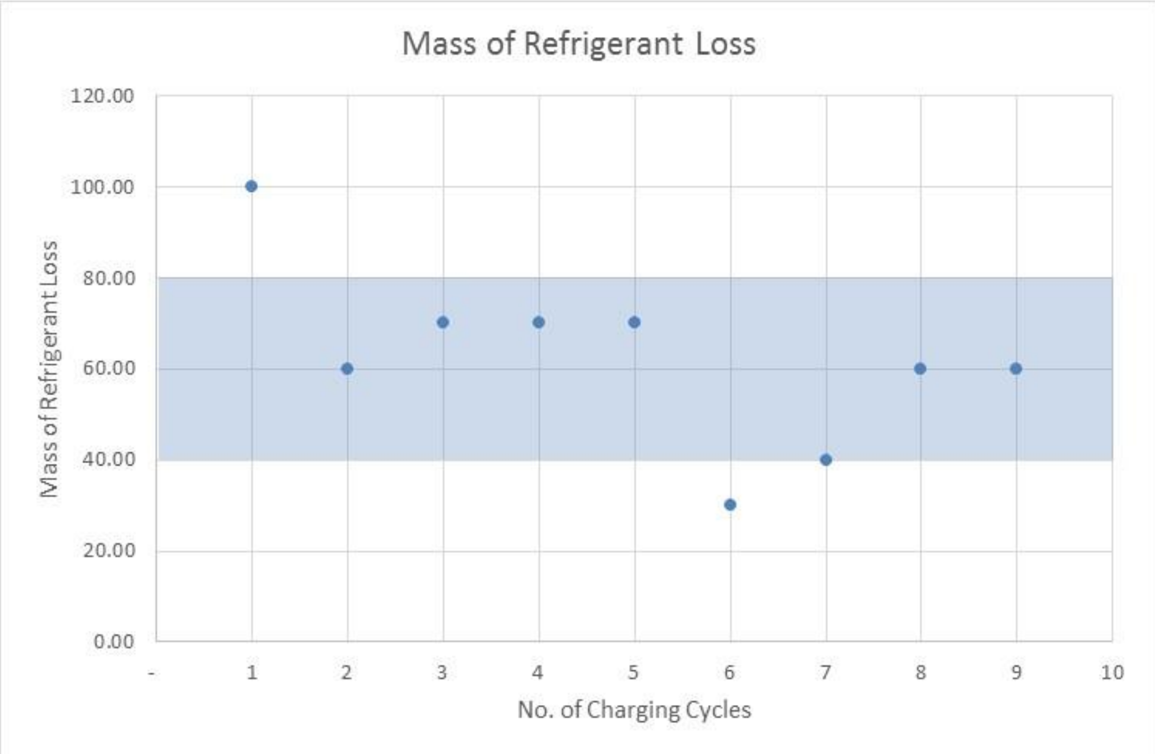

Figure 2: Results from Recharging Tests

The results indicate that the loss of refrigerant remained within a relatively limited range across the number of tests. These figures are shown within the highlighted part of Figure 2. The average overall loss during the 9 cycles was 62 grams. It is important to note that measurement points 1 and 6 were considered as being the 'extremes' - i.e. that results above 80g loss were due to being less careful and results below 40g were due to being extra careful. Neither of these scenarios are likely during a standard evacuation and recharge process. Therefore the range of refrigerant lost for each process of evacuation and recharge was taken as shown in Table 17.

Recharge Losses	Loss of Charge (kg)
Low	0.040
Central	0.062
High	0.080

Table 17: Recharge Losses

In order to utilise these values in the model it was also necessary to determine the frequency of testing and, for each test, how often this resulted in a leak being detected and, therefore, in the installation being recharged. The frequency of testing was determined based on the current EU F-gas regulations which have been discussed in detail in Section 2.1. The frequency of leaks being detected was identified from the log-book analysis data. This revealed that 8.97% of tested non-domestic and 10.00% of domestic installations had leaked and lost sufficient refrigerant to require recharge. These figure (8.97% and 10.00% respectively) were therefore utilised in the model.

6.2.5 Refrigerant Reclamation

During repair of heat pump installations, the refrigerant is pumped-down to a recovery cylinder to be re-used in the same installation or to be reclaimed for recycling. The cylinders of reclaimed refrigerant will then be transported between the site and back to reclamation organisations (which in some cases are also distributors). The loss that can potentially occur from such bottles is similar in nature as that described for the transport of bottles from distributor to the site. It was intended to conduct an identical piece of research to that planned for the transport of bottles from distributor to site for transport of reclaimed refrigerant. Due to the same challenges identified above, however, this was not possible within the scope of this study. Nonetheless, such research is feasible and could be conducted to determine the losses from this stage of the lifecycle.

7.0 Impact of Reduced Charge on Heat Pump Performance

In assessments of heat pump performance the issue of whether there is a performance drop, due to the installation operating with reduced levels of charge, is often excluded from any analysis. For this study, therefore, a set of practical tests were devised and conducted to identify the level of performance loss associated with varying levels of reduced charge.

In particular, the aim of this research was to identify the reduction in Coefficient of Performance (COP) values when the heat pump is operating at lower levels of refrigerant charge to provide a clear indication of any associated reduction in efficiency. It should be noted, however, that due to a lack of suitable data relating to current and future charge levels these impacts are not taken into consideration within the wider modelling of leakage undertaken in Section 8.0.

7.1 Approach

A set of experiments were conducted whereby the same ground source heat pump (a Water Furnace EKW130) was operated for a certain period at differing levels of charge and its performance (COP) measured at each level. The heat pump was located at LSBU. It was operating in an uncontrolled environment whereby it was working as part of a wider set of heat pumps to provide heating and cooling to a building exposed to temperature variations that were not controlled in the test. The heat pump had a nominal capacity of 125kW in cooling mode and 120kW in heating mode and was charged with the refrigerant blend R410A.

A 'ClimaCheck' performance analyser (PA Pro II) was connected to the heat pump and recorded measurements at two minute intervals during the monitoring periods. Energy meters were used to compute the heating (or cooling) energy flow, based on the volumetric flow rate of the heat carrier fluid, its specific heat capacity (taking into consideration of the change of density and heat capacity with temperature) and the temperature difference between input and return flow. The hourly average heating and cooling energy flow data were logged as part of the data recording process. The electricity consumption of the compressor was also recorded in order to facilitate calculation of the COP.

The following charges were used during the experiments:

- 100% charge (this was tested twice; once at the start and once at the conclusion of the tests to verify the results);
- 60% charge;
- 75% charge; and
- 90% charge.

The first test was conducted at 100% over a 24 hour period. The refrigerant was then extracted and the unit recharged to 60% of capacity. Once the level stabilised, the heat pump was monitored over the course of more than 24 hours. Additional refrigerant was then added to the pump to achieve 75% charge and 24 hour monitoring was again conducted. This process was repeated until a final set of results for 100% charge were obtained. From the hourly average heating and cooling energy delivered by the pump and the associated energy consumptions it was possible to calculate the COPs associated with the different levels of charge.

7.2 The Impact of Outside Air Temperature

When the outside air temperature dropped below the heating set point of 14°C, or rose above the cooling set point of 17°C, the LSBU heat pump operates in heating or cooling modes respectively. If the outside air temperature is between those two set points, the heat pump does not operate. The testing was carried out with an uncontrolled external environment (i.e. the outside air temperature was below and above the heating and cooling set points for only limited periods). Consequently continuous operation of the heat pump only occurred for short times (i.e. a few hours a day) during the monitoring periods. Each monitoring period lasted for just under 48 hours, except for the period associated with 75% charge which lasted for just under 72 hours due to the presence of a weekend during the testing schedule.

Table 18 provides a summary of whether heating or cooling operation of the heat pump occurred for a period that was long enough to extract meaningful data at the different refrigerant charge levels. The corresponding average outside air temperatures that were recorded during the heating and cooling periods are listed in Table 19. The information in Table 18 shows that while the installation was being monitored with a 75% refrigerant charge, no operation of the heat pump occurred (in either in heating mode or cooling mode) even for a short period. As a result, as discussed in Section 7.3, we were not able to derive any results for this level of charge.

Operation Mode	100% Charge (no.1)	60% Charge	75% charge	90% Charge	100% Charge (no.2)
Heating	✓	✓	✗	✓	✗
Cooling	✓	✓	✗	✓	✓

Table 18: Successful Modes of Operation during Test

Operation Mode	100% Charge (day 2)	60% Charge	75% charge	90% Charge	100% Charge (day 11)
Heating	13.5°C	13.6°C	N/A	13.6°C	N/A
Cooling	20.2°C	17.9°C	N/A	17.4°C	18.3°C
Heating	5hrs	4hrs	N/A	4hrs	N/A
Cooling	8hrs	3hrs	N/A	3hrs	8hrs

Table 19: Average outside Air Temperatures and Running Times during Test

7.3 Results from Charge Tests

Figure 3 shows the relative heating and cooling COPs of the heat pump (normalised to 100%) with varying refrigerant charge level and Table 20 illustrates the absolute COP values measured. The absolute COP values are high due to the relatively low difference in temperature between the inside space and outside which occurred at the time of the tests which were held in autumn 2013.

The relative results show that during both heating and cooling operation of the heat pump at reduced charge levels resulted in significantly lower relative COPs. For the installation assessed in this study, a refrigerant charge reduction of 10% led to a relative COP reduction of about 3% in heating and 15% in cooling operation respectively. Undercharging the heat pump by 40% reduced the relative COP by around 45% in heating mode and 24% in cooling operation. For the heating mode in particular this is a very significant reduction in performance.

Operation Mode	100% Charge	60% Charge	75% Charge	90% Charge
Heating	9.1	5.0	N/A	8.8
Cooling	14.9	11.3	N/A	14.1

Table 20: Actual COP from Low Charge Tests

The information presented in Figure 3 indicates that the performance of a heat pump operating in heating mode is not significantly compromised by small amounts of charge loss. Below 85% charge, however, performance begins to dip significantly. Therefore for installations which have previously experienced small leakage rates it is unlikely that there will be any significant reduction in efficiency unless further leakage occurs. Where leaks of greater severity occur, however, leading to 15% reduction in charge or greater, there is likely to be a significant drop in performance that would lead to significantly increased electricity usage to deliver the same heat output, thereby reducing both the economic and climate change benefits of the heat pump.

Whilst we have not attempted to model the impact of any scenarios in which there might be an overall fall in heat pump performance (SPF), the results of this analysis suggest that the climate change benefits of heat pumps presented in Section 8.0 might be slightly overstated. This is because some installations are likely to be operating less efficiently than under our central SPF assumptions.

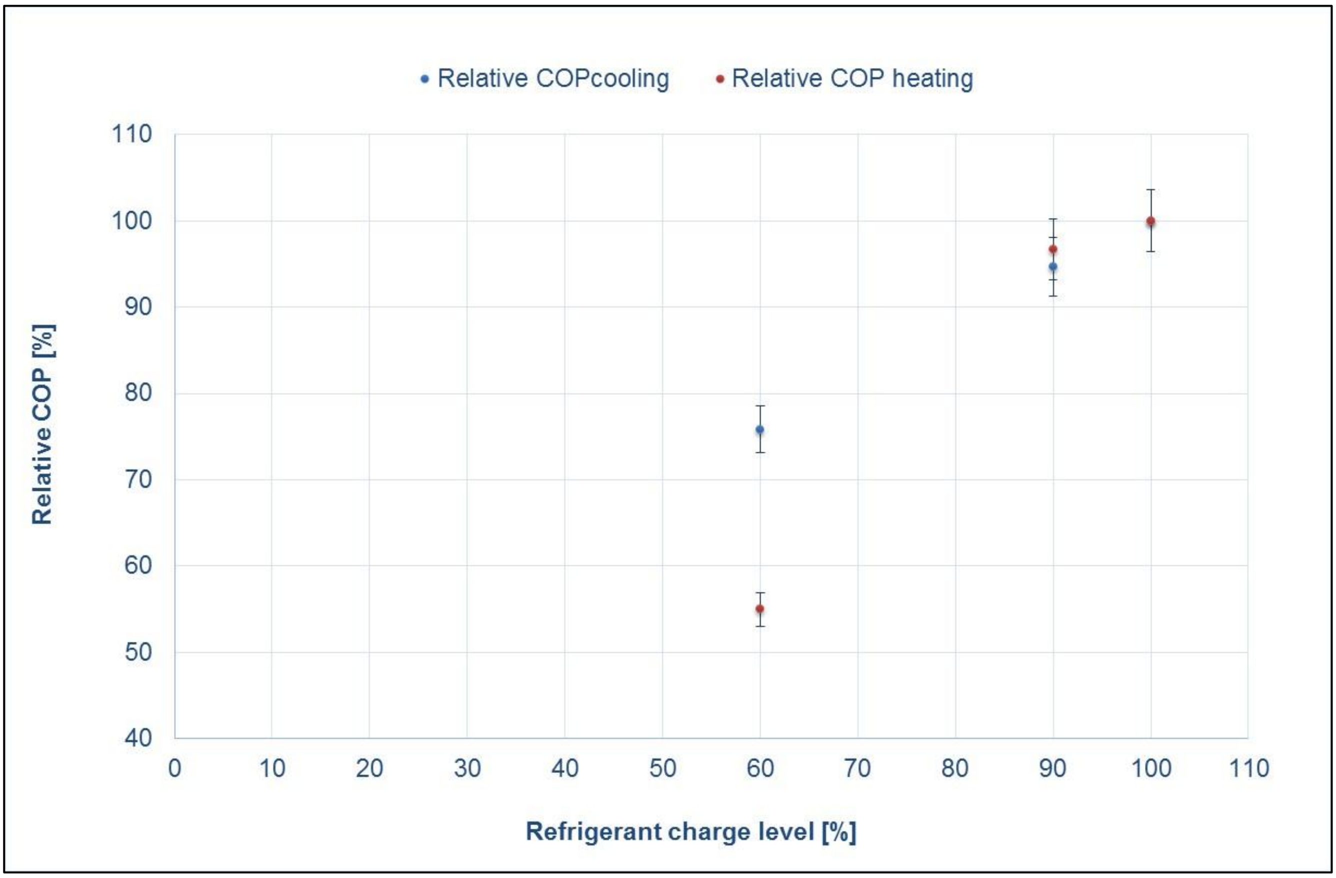

Figure 3: Relative Change in Heating and Cooling COPs with Varying Refrigerant Charge

7.4 Performance Comparison with Previously Reported Data

Several other studies into the effects of reducing refrigerant charge on heat pump performance have been undertaken as interest in the effects of charge reduction rise.[48] One study (Fernando, 2004) undertook a low refrigerant charge laboratory test on a small water-to-water heat pump.[49] Other investigations have included a charge optimisation study of a reversible water-to-water heat pump (Corberan, 2008) and an investigation of the impact of refrigerant charge on heat pump performance (Kim, 2012).[50] [51] To compare the results of these studies with the results from the tests undertaken on the LSBU heat pump, we have plotted the relative COPs from the 'heating mode' results from all studies on a single chart. As shown in Figure 4, this demonstrates a similar overall trend in relative COP change due to reduced charge levels.

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[48] Oltersdorf, T., Braungardt, S., and Sonner, C. (2013) Refrigerant Charge in Heat Pumps: Charge Inventory Analysis and the Advent of Charge Reduction, *IEA Heat Pump Newsletter*, Vol.31, No.3, pp.15–19

[49] Fernando, P. (2004) Propane Heat Pump with Low Refrigerant Charge Design and Laboratory Tests, *International Journal of Refrigeration*, Vol.27, No.7, pp.761–733

[50] Corberan, J. (2008) Charge Optimisation Study of a Reversible Water-to-Water Propane Heat Pump, *International Journal of Refrigeration*, Vol.31, No.4, pp.789–798

[51] Kim, W., and Braun, J. (2012) Evaluation of the Impacts of Refrigerant Charge on Air Conditioner and Heat Pump Performance, *International Journal of Refrigeration*, Vol.35, pp.1805–1814

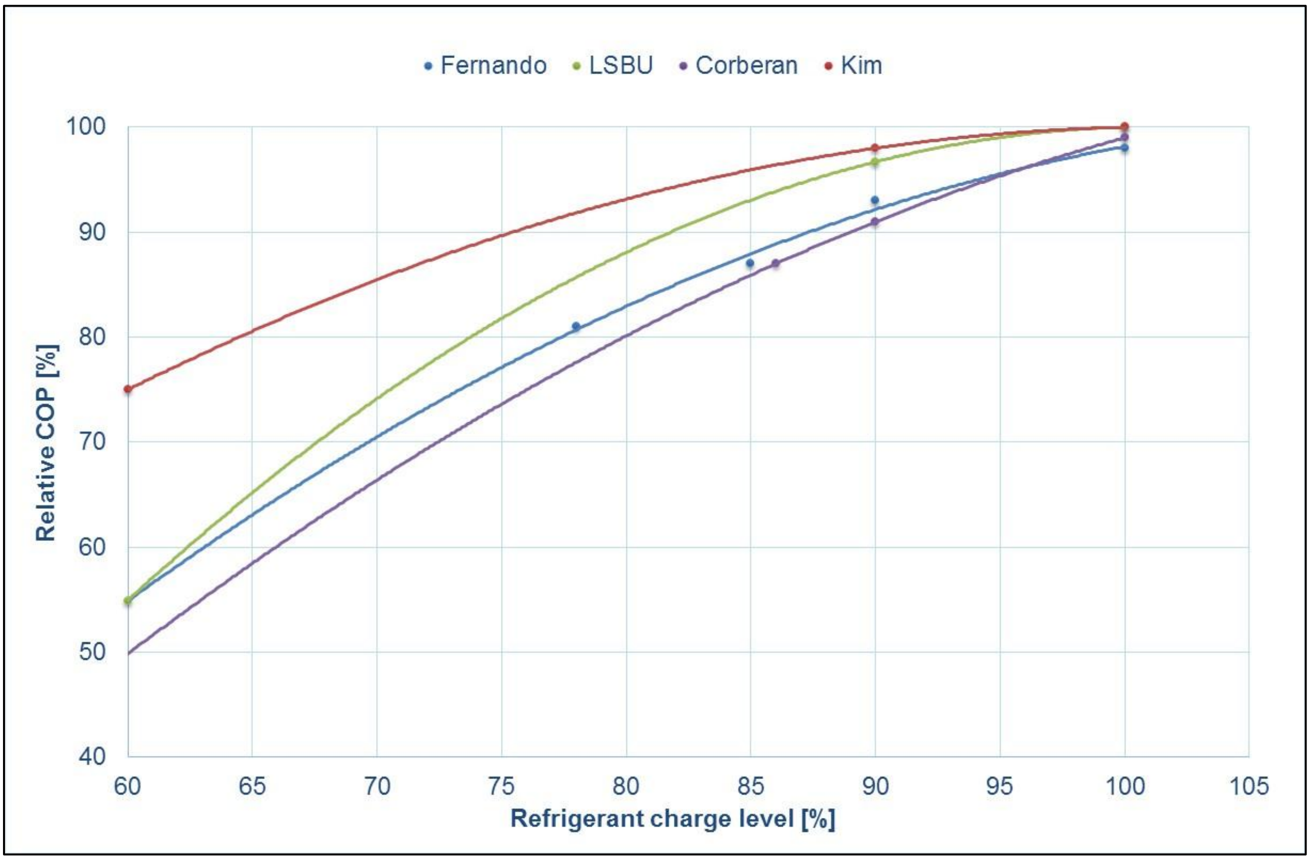

Figure 4: Comparison of Heating Results with Similar Studies

When comparing these results it should be noted that the other studies were undertaken in laboratory environments, whereas the testing for this study was carried out in an uncontrolled environment (varying external ambient temperature). Whilst this latter approach may introduce uncertainties into the study, it does offer a more accurate assessment of the performance of a heat pump in actual operating conditions and therefore the values obtained in this study are of particular relevance to the potential performance of heat pumps across the UK.

8.0 Assumptions used to Model Environmental Benefits and Impacts

The focus of this Section is upon the assumptions used to model carbon dioxide equivalent (CO_2e) impacts, albeit where relevant data is available, we have also developed assumptions relating to other environmental impacts. Modelling was conducted to quantify the following:

- The net change in CO_2e emissions resulting from the use of heat pumps rather than other energy sources to 2050 (but with core focus to 2020); and
- The net effect of other environmental impacts resulting from the leakage of refrigerants from heat pumps.

The model structure is shown in Figure 5. With regard to the CO_2e factors for heat pumps and heat pump deployment, it should be noted that the inputs to the model drew on existing work from DECC wherever possible.

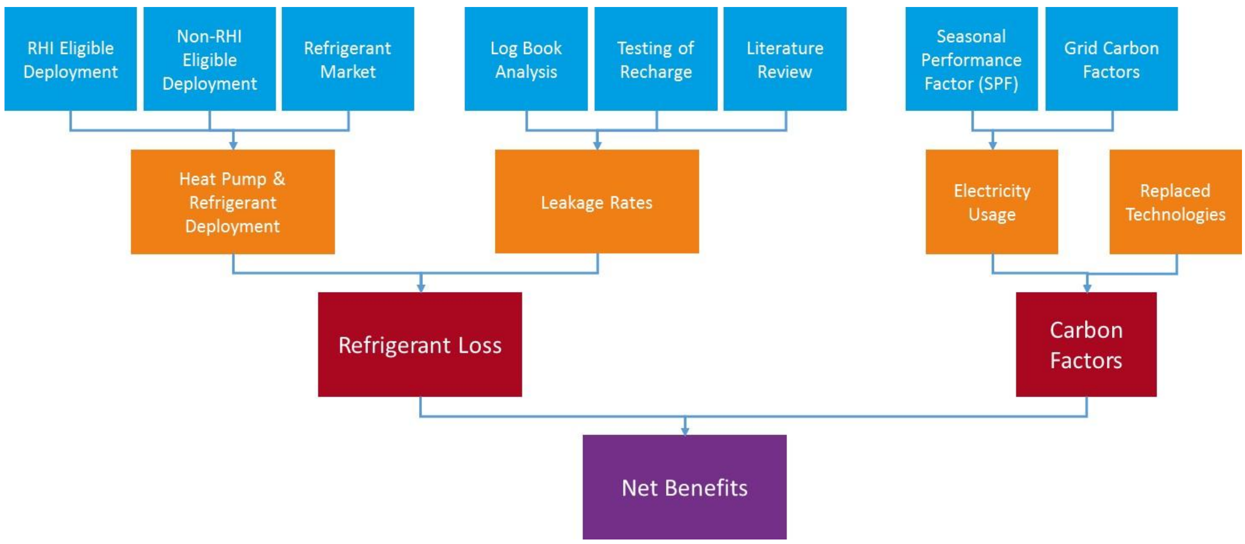

Figure 5: Structure of Model

It should be noted that throughout Sections 8.1 to 8.3, which detail our assumptions relating to heat pump deployment, refrigerant deployment, and benefits of displacing alternative heating technologies, we have also, to facilitate sensitivity analysis, included 'low' and 'high' scenarios around our central assumptions for each key parameter.

8.1 Heat Pump Deployment

There is significant growth predicted by DECC for the heat pump sector over the coming years to 2020, in large part driven by the RHI (for both domestic and non-domestic installations), as discussed in Section 3.1. This greater level of deployment will lead to a significant increase in the quantity of refrigerant use (and thus likely levels of refrigerant leakage) in the UK. Heat pump deployment is therefore the most important variable in the model developed for this study, as increased deployment amplifies the impact of any leakage, along with any climate change benefits. As the renewable heating market and the RHI are at an early stage, however, there is some uncertainty as to the full potential and likely deployment profile of the technology.

Essentially, for this modelling, we have used three categories of heat pump:

- Installations not-eligible for RHI payments;
- Installations eligible for, but not supported by RHI payments; and
- Installations supported by the RHI.

8.1.1 Heat Pump Deployment Modelling Assumptions to 2020

The modelling of deployment drew on the following data sources:

- Published market estimates;[52]
- Unpublished industry sales figures;
- RHI projections;[53] [54] and
- AAHP deployment projections.[55]

These data were then combined with assumptions regarding the growth of the market. These assumptions were made for the following market segments:

- Growth rates for non-RHI eligible heat pumps up to 2020/21; and
- Growth rates for RHI-eligible heat pumps for which RHI is not claimed up to 2020/21.

For AAHPs (which are not currently supported by the RHI), it was also necessary to make assumptions regarding the proportion of the market that related to units that were:

- Heating only;
- Heating led (with some additional cooling); or
- Cooling led with some additional heating.

These assumptions for AAHPs led to significantly reduced heat pump deployment numbers compared to the broader market figures for small air conditioning units, which reflects the current usage of AAHP units in the UK.

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[52] Heat pump baseline survey information undertaken by Ricardo AEA for DECC

[53] DECC (2013) *Impact Assessment: RHI Tariff Review, Scheme Extensions and Budget Management*, September 2013, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/263582/Impact_Assessment_RHI_Tariff_Review_Extensions_and_Budget_Management_Dec_2013.pdf

[54] DECC (2012) *Impact Assessment: Changes to the Current Non-Domestic Renewable Heat Incentive Scheme*, September 2012, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/66606/6444-impact-assessment-on-changes-to-the-current-nondo.pdf

[55] ICF International (2011) *Development of the GHG Refrigeration and Air Conditioning Model: Final Report*, Report for DECC, December 2011

Number of Heat Pumps Deployed

The results of this modelling to 2020/21 are shown Figure 6 (excluding AAHPs) and Figure 7 (including AAHPs). This shows the total projected number of heat pumps for both non-domestic and domestic scale installations (all heat pumps in operation in any given year). When viewed together, these figures show that AAHPs represent a very significant proportion of the market for heat pumps. This is such that the likely growth in the market driven by the RHI is somewhat 'masked' by AAHPs. Nonetheless, both Figures show a clear trend to increasing numbers of heat pumps in the UK up to 2020/21. Without AAHPs, the modelling suggests that between 270,000 and 600,000 installations will become operational by 2020/21, whilst if AAHPs are included, this number rises to between 2,000,000 and 3,300,000 within the same period. The range of results reflects the current uncertainty regarding heat pump deployment.

The number of installations does not give a specific indication of the heat generated as each different type of pump will generate a different amount of heat each year. The reason for highlighting heat pump installations is that the quantity of refrigerant employed is determined by the number and type of heat pumps in use, and is poorly correlated to the amount of heat generated. It should be emphasised that these numbers are projections developed in discussion with DECC for the specific purposes of this study. Detailed discussion of the expected heat generated under the RHI can be found in DECC's related Impact Assessments (IAs).[56]

[56] DECC (2013) Impact Assessment: RHI Tariff Review, Scheme Extensions and Budget Management, September 2013, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/263582/Impact_Assessment_RHI_Tariff_Review_Extensions_and_Budget_Management_Dec_2013.pdf; DECC (2012) Impact Assessment: Changes to the Current Non-Domestic Renewable Heat Incentive Scheme, September 2012, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/66606/6444-impact-assessment-on-changes-to-the-current-nondo.pdf

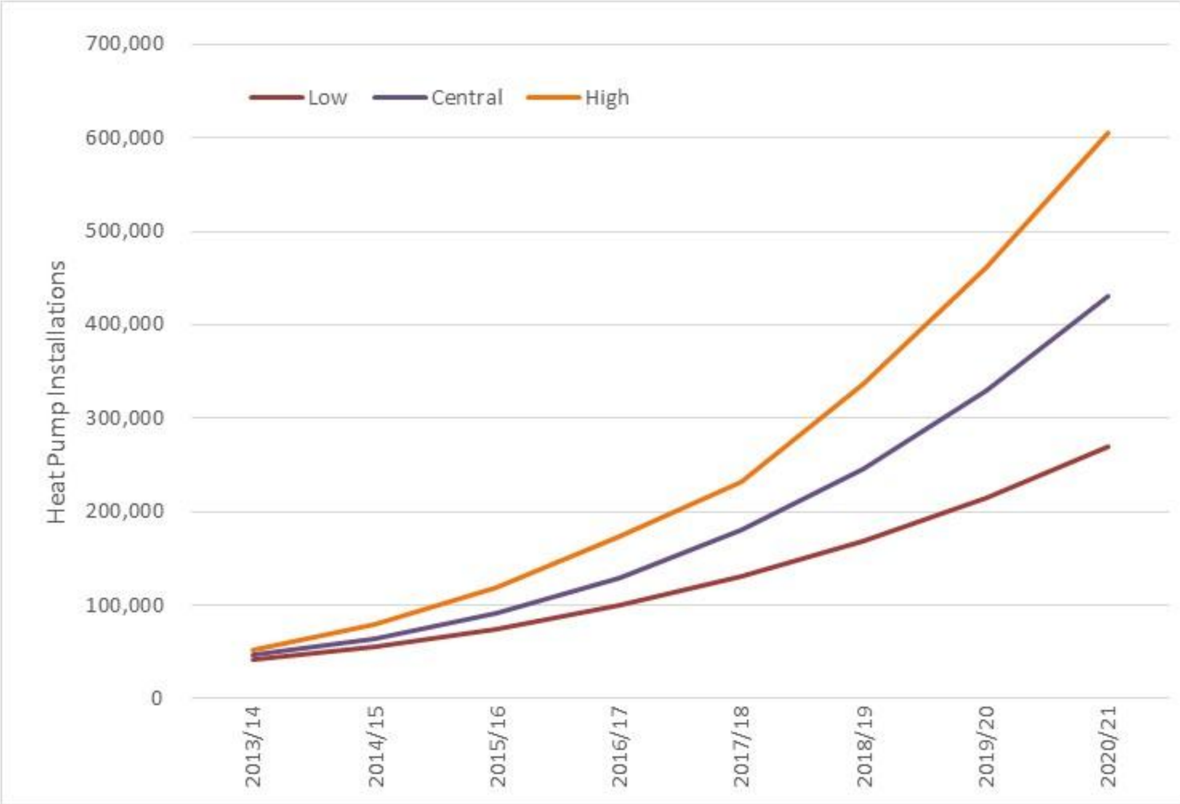

Figure 6: Cumulative Heat Pump Installations to 2020/21 (Excluding Air to Air)

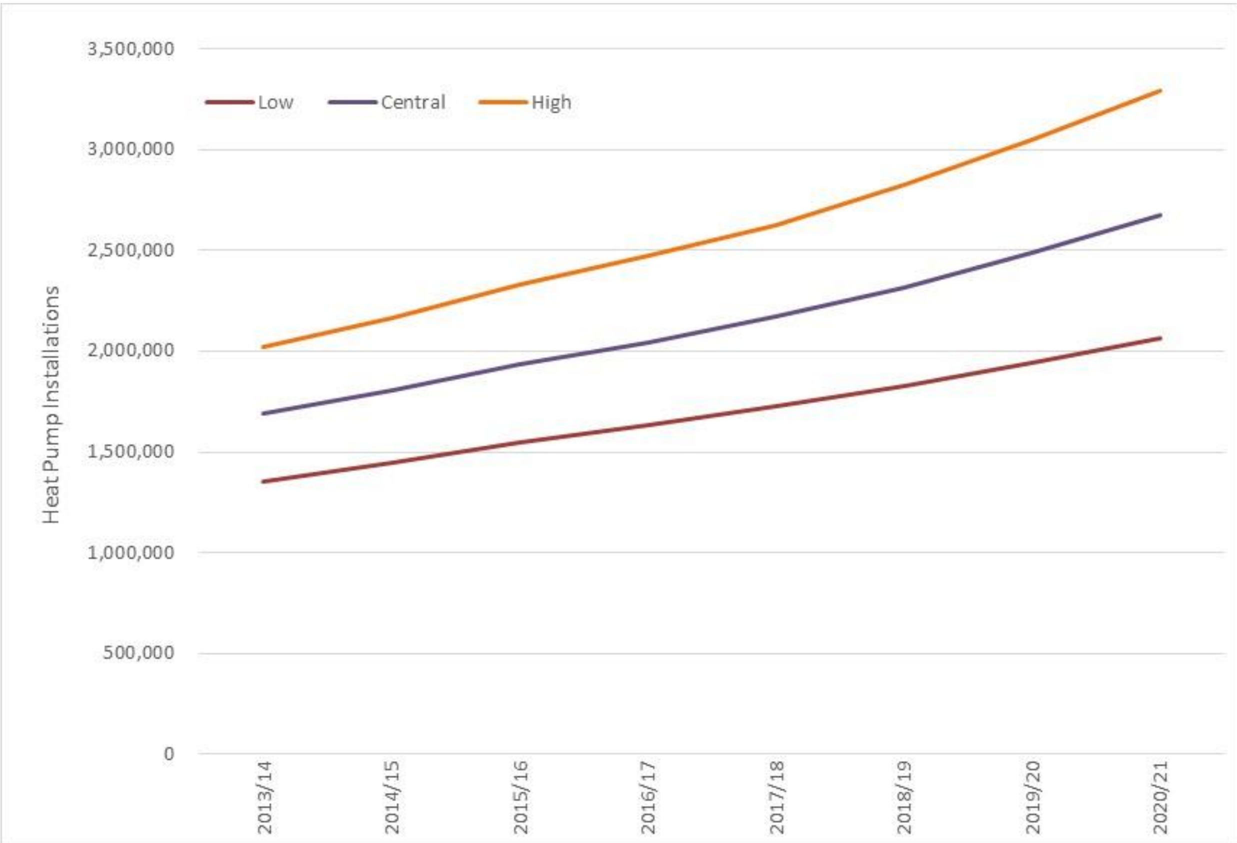

Figure 7: Cumulative Heat Pump Installations to 2020/21 (Including Air to Air)

8.1.2 Heat Pump Deployment Modelling Assumptions to 2050

Modelling to 2050 was based on the use of annual growth rates for the whole market. Unlike the growth rates used for the market prior to introduction of the RHI which applied to the cumulative market, growth figures were identified for the change in new installations in each year. The reason for this difference is that:

1. The figures available prior to the introduction of the RHI were largely in cumulative form; and
2. If the growth is modelled in this manner post 2020/21 there is significant fluctuation in annual deployment figures. By utilising growth figures for annual deployment it is possible to achieve a realistic growth curve which better reflects the likely behaviour of the market.

Number of Heat Pumps Deployed

The results of the above approach are shown in Figure 8 (excluding AAHPs) and Figure 9 (including AAHPs). Once again the very significant contribution of AAHPs can be clearly seen, with ranges between 800,000 and 2,100,000 heat pumps without AAHP installations, and 2,900,000 to 5,200,000 including AAHPs. The very wide ranges reflect the uncertainty of modelling the market over such a long timeframe, and these estimates could change as the markets develop in response to wide variety of variables.

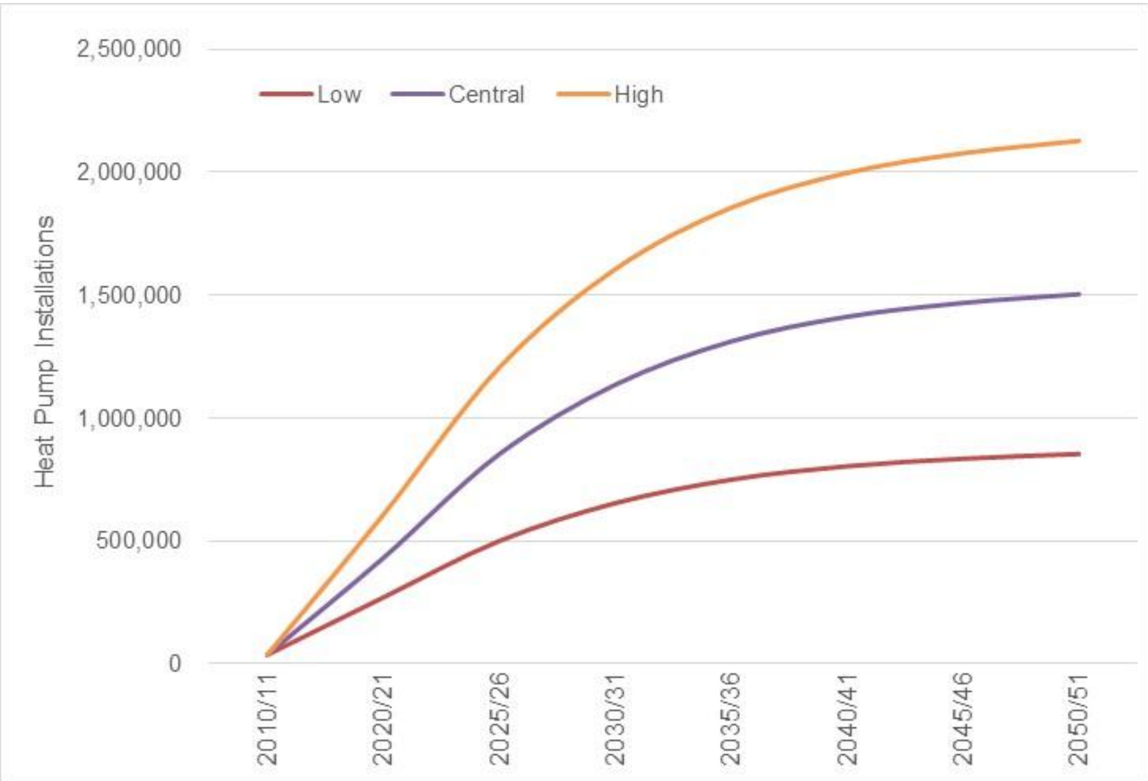

Figure 8: Cumulative Heat Pump Installations to 2050/51 (excluding AAHPs)

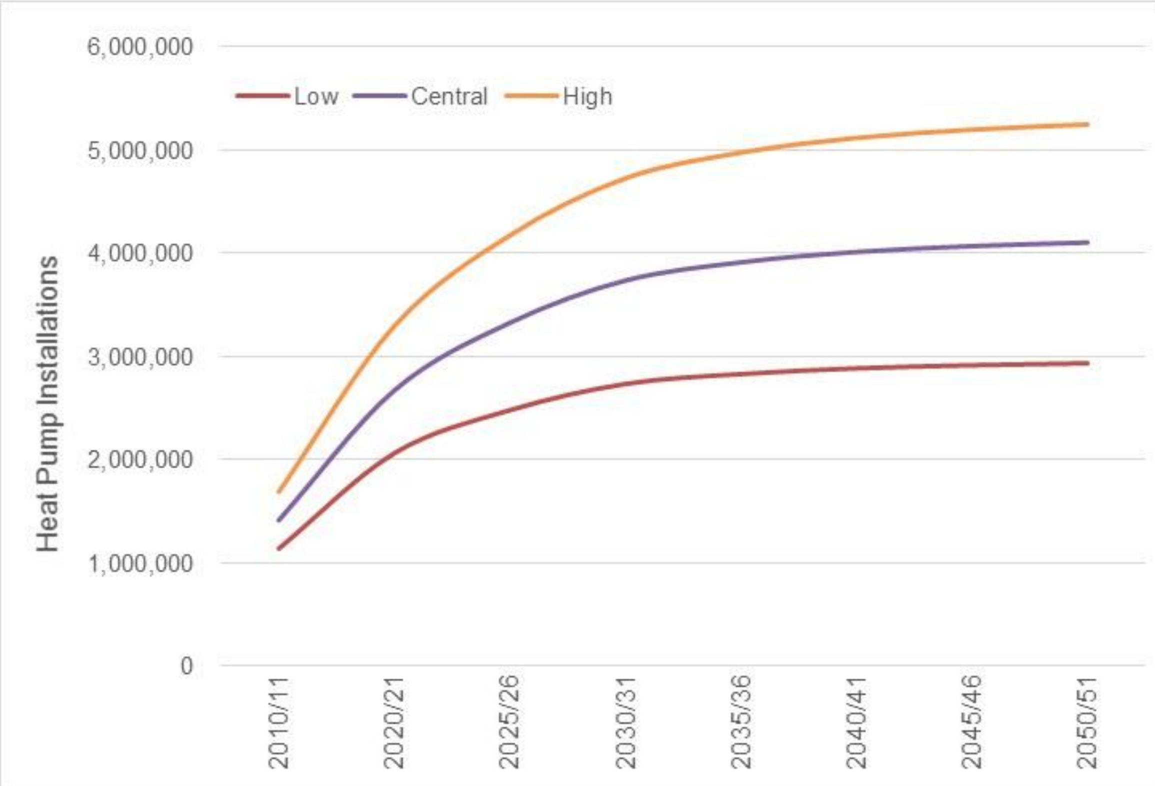

Figure 9: Cumulative Heat Pump Installations to 2050/51 (including AAHPs)

As with the figures for deployment to 2020/21, these results were 'sense checked' by assessing the maximum new installations in any given year. This reaches around 120,000 installations per annum between 2040/41 and 2050/51, many of which are replacement heat pumps. This can be compared to a recent figure of 100,000 units sold in one year in France which indicates that these are realistic projections, especially considering that at this point the replacement market should be a significant portion of overall sales as the market becomes more mature. The modelled deployment was also sense-checked against the number of off-gas grid households, which is the initial primary target market for the RHI.

Nonetheless there remains significant uncertainty regarding the market to 2050, and this is indicated by the differing market projections that exist, in particular the projected domestic heat pump market identified in DECC's Heat Strategy, which indicates that heat pumps could provide around three quarters of all domestic heating demand by 2050.[57]

8.2 Refrigerant Deployment

The modelling of the number of heat pumps in operation was conducted in order to determine the quantities of refrigerant installed, and thereby the leakage of refrigerant occurring from heat pumps. The quantity and type of refrigerant installed in heat pumps at any one time is determined by the following:

- Number of heat pumps installed (taken from above analysis);

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[57] DECC (2013) *The Future of Heating: Meeting the Challenge*, March 2013

- Refrigerant capacity of heat pumps;
- Mix of refrigerants in use at the time of installation; and
- The lifespan of a heat pump.

These parameters are modelled together to determine the leaked quantity of each refrigerant, which is multiplied by the GWP of that refrigerant to calculate the emissions in $kgCO_2e$. Subsequently, this impact is subtracted from the $kgCO_2e$ benefits (as described in Section 8.3) to identify the net benefit of heat pump operation.

8.2.1 Refrigerant Capacity of Heat Pumps

The assumed refrigerant capacities of heat pumps were derived directly from the log-book analysis described in Section 5.0 for all heat pumps except AAHPs, and resulted in values that are shown in Table 21. Whilst non-domestic heat pumps have been sub-divided into three distinct sizes, the mean charges were very similar and so the overall mean was used in the subsequent modelling. The AAHP capacity figure was taken from the same dataset from which the deployment data, described in Section 8.1, was obtained.[58]

Installation Type	Size	Mean Refrigerant Charge (kg)	Overall Mean Refrigerant Charge (kg)
Non-domestic	Less than 50kW	23.53	24.53
	50 up to 250kW	26.36	
	Equal to or greater than 250kW	29.50	
Domestic	All	3.30	3.30
AAHP	All	1.50	1.50

Table 21: Heat Pump Charge

8.2.2 Assumed Mix of Refrigerants and Heat Pump Lifespan

The mix of refrigerants in use at the point of a new pump being installed is determined by the availability, cost, and technical compatibility of each refrigerant with the heat pump unit. As described in Section 2.2, the most significant driver behind the changing mix of refrigerants is the F-Gas regulations. These constraints on HFC use in turn drive the development and production of new or different refrigerants, for example, natural refrigerants CO_2 and hydrocarbons, new HFOs, and the associated heat pump technologies that can operate with them.

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58 ICF International (2011) *Development of the GHG Refrigeration and Air Conditioning Model: Final Report*, Report for DECC, December 2011

The mix of refrigerants installed in a given year will have an impact over a longer period of time, which is largely determined by the lifespan of a heat pump. Therefore, the mix of refrigerants installed will only change gradually as old pumps are replaced by new ones with a mix of refrigerants that reflects market dynamics at any given point in time. For example, if the mean lifespan of a heat pump is taken to be 20 years, it will take 20 years beyond the final deployment of a particular refrigerant to remove this refrigerant from operation (unless regulation specifically bans the ongoing use in existing installations). Only at the point of replacement of an installation will the refrigerant used change to reflect the current mix of refrigerants. The model reflects these market characteristics by using different assumptions for the overall refrigerant mix in line with expected lifespans.

By combining all of the above factors, the model estimates the total quantity of each type of refrigerant installed in heat pump installations for any given year. This can then be used to determine the impacts from any quantities of refrigerant that are assumed to be leaking. The proportions of gases being installed in new heat pumps between 2005/06 and 2050/51 is summarised in Table 22 for our central scenario, which is based on the current proposed revisions to the F-Gas Regulations. The nature of this assessment (i.e. there are a number of variables, all of which cannot be predicted to any great accuracy) is that the projections are speculative; although the important balance is between HFCs (e.g. R410A) and alternative refrigerants (e.g. CO_2 and the new HFOs) as HFCs have a GWP many times greater than the alternatives.

Refrigerant Market Share	2005/06	2010/11	2015/16	2020/21	2030/31	2050/51
404A	4%	2%	0%	0%	0%	0%
407C	44%	30%	20%	10%	0%	0%
410A	50%	66%	75%	50%	15%	0%
134a	2%	2%	0%	0%	0%	0%
HCs	0%	0%	2%	16%	43%	50%
CO_2	0%	0%	0%	4%	13%	25%
HFOs	0%	0%	3%	20%	30%	25%

Table 22: Central Assumption for Refrigerant Mix to 2050

To test the sensitivity of our central assumptions to changes in the assumed refrigerant mix, we modelled a ‘low’ scenario, which assumes the HFC limitations proposed within F-Gas regulations come into force later this decade, albeit with these being less onerous than currently predicted. We also modelled a ‘high’ scenario, which assumes that the F-Gas regulations are implemented on time and are stricter in terms of phasing out HFCs. Following publication of the agreed text within the F-Gas Regulations during the course of this study (and subsequent to us running these sensitivities), however, it should be noted that both of these alternative scenarios are less likely to occur than the central scenario.

There is also some uncertainty with regard to how the use of both natural refrigerants and new HFOs will develop. We have therefore modelled variations in this development profile to test the sensitivity of the results to such changes.

8.3 Benefits from Displacing Other Heating Technologies

To put the CO_2e impact of refrigerant loss in context, the CO_2e *benefits* which can be attributed to the projected future deployment of heat pumps in the UK have been modelled. These benefits are largely the result of lower CO_2e emissions when compared to the technologies that they displace. Therefore, defining the combined 'carbon intensity' of the displaced technologies is critical to identifying any CO_2e saving. At the same time, however, heat pumps require electricity to operate, which must usually be drawn from the national electricity grid, for which a CO_2e emissions factor must also be used. As a result, the carbon benefit attributed to heat pumps should be calculated net of these emissions from electricity use. These calculations were performed using DECC's own estimates of heat demand, SPFs and grid carbon intensity factors. A summary of the carbon factors for heat pumps is provided in Table 23.

Technology		2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21
Non-Domestic	AWHP	0.10	0.07	0.08	0.10	0.11	0.13	0.14	0.16	0.16	0.18
	GSHP	0.11	0.09	0.10	0.11	0.12	0.15	0.15	0.17	0.17	0.19
Domestic	AWHP	0.07	0.05	0.06	0.07	0.08	0.10	0.11	0.12	0.13	0.14
	GSHP	0.22	0.22	0.22	0.22	0.21	0.21	0.20	0.20	0.20	0.19

Table 23: Carbon Intensity Factors to 2020/21 ($kgCO_2/kWh$)

8.3.1 Heat Delivered by Heat Pumps

In order to determine the quantity of benefit, it is also necessary to determine the quantity of heat delivered by each installation type over the course of a year. These assumptions have been drawn from DECC's RHI projections and are shown in Table 24, which shows example heating demand figures for 2015/16 under our central scenario. Whilst the modelled values change with time (due to changing characteristics of the buildings being heated) and by scenario, the relative changes are minor.

Installation Type		kWh / year
Non-Domestic	AWHP	161,885
	GSHP	332,880
Domestic	AWHP	10,151
	GSHP	25,387

Table 24: Central Mean Heating Demand in 2015/16

8.3.2 Seasonal Performance Factors

The performance of a heat pump is measured over the course of a year by the SPF. This is one of the constituents of the calculations to determine the carbon factors. SPFs reflect the ratio of output heat to input energy (electrical energy for the vast majority of heat pumps). The higher the SPF, the greater the quantity of heat for a given amount of electricity. It is anticipated that over time the SPFs of heat pumps in the UK will improve as technologies improve.

8.4 Non CO2e Impacts

As highlighted above, the potential environmental impact of refrigerants extends beyond climate change issues, which are broadly captured by CO_2e calculations. As described in Table 11, refrigerants have a number of impacts beyond CO_2e, although these are often difficult to quantify, and related research is very limited.

In order to identify the other environmental impacts of leaked refrigerants a number of Life-Cycle Assessment (LCA) databases were interrogated for information on refrigerants. These databases included:

- EcoInvent 2.2;[59]
- Waste and Resources Assessment Tool for the Environment (WRATE);[60]
- PE International's Gabi tool;[61] and
- European Reference Life Cycle Database (ELCD).[62]

Of the databases interrogated, only EcoInvent currently holds any relevant data on refrigerants. Additionally there are a number of issues associated with the nature of the data held in these databases, which provide challenges in translating this into quantified impacts:

1. Data held in existing databases refers to the impact of manufacture of a unit of the substance in question. Unless a specific dataset is developed for the process of leakage, the information held in the database does not address the impact of leakage directly. Since the impact of production and leakage of refrigerants are likely to be significantly different in nature and scale, it is not appropriate to utilise LCA data for leakage modelling;

2. Whilst for atmospheric impacts, such as CO_2e and ODP there is relative certainty that the release of a kg of substance will have a particular effect, for other impacts (e.g. eutrophication) the impact of a leaked kg of refrigerant may have widely differing impacts due to the nature and location of the leak. It is not possible to identify with accuracy the proportion of a leak that would enter specific ecosystems (e.g. marine environments). Consequently, the impact of leakage of a 'generic' kg of refrigerant cannot be robustly quantified; and

3. Whilst EcoInvent holds information on CO_2 and R134a, other refrigerants utilised in heat pumps are not included and therefore only a very partial picture can be obtained.

Given the scope and nature of these challenges it is not possible to utilise LCA data on the environmental impacts of refrigerants to analyse the impact of refrigerant leakage in a robust manner. If modelling of non-CO_2e impacts were to be conducted with these figures, the results would be misleading due to significantly raised impacts.

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59 See http://www.ecoinvent.org/

60 See http://www.environment-agency.gov.uk/research/commercial/102922.aspx

61 See http://www.gabi-software.com/uk-ireland/index/

62 See http://eplca.jrc.ec.europa.eu/?page_id=126

8.4.1 Likely Impacts

Whilst it is not possible to model the impact of non-CO_2e impacts with any accuracy, it is possible to identify the impacts that are of greatest concern, based on the LCA data. It is reasonable to assume that where the production of a refrigerant has minimal environmental impact, the subsequent leakage of the refrigerant will similarly have a small impact.

Figure 10 shows the normalised impact of 1kg of liquid CO_2 and 1kg of R134a. The normalisation process involves comparing the impact of each substance to an overall reference situation. The resulting figure clearly indicates that the impact of CO_2 used as a refrigerant is minimal except for a marginal negative Marine Water Aquatic Eco-Toxicity value. By contrast R134a has notably large impacts for Marine Water Aquatic Eco-Toxicity and Ozone Depletion Potential (ODP), although all other non-CO_2e impacts are also negligible. The ODP result highlights the difference between impact of production and leakage, as leakage of R134a into the atmosphere is known to have zero ODP. The 'non-zero' result for ODP is caused by the impact of the processes and materials used to produce R134a, not R134a itself. Therefore to use a figure derived from LCA databases would give an incorrect indication of the impact of leakage from heat pumps on the Ozone layer.

Excluding ODP leaves only Marine Water Aquatic Eco-Toxicity as notably significant besides CO_2e impacts. The eco-toxicity impacts are not as clearly defined in existing LCA databases when compared to ODP and Climate Change impacts, which are much better understood. In particular, ecosystems are highly diverse and therefore it is not possible to provide a single value for toxicity that will be accurate for all locations.

As discussed above, further to this uncertainty is the unknown proportion of leaked refrigerant that will actually enter the ecosystem concerned. Refrigerant leakage in vapour form will likely be emitted directly into the atmosphere. It is therefore reasonable to assume that it will not have a significant toxicity impact on marine (or indeed other) ecosystems. Leakage that occurs in liquid form is likely to remain in and around the point of leakage unless it is able to drain into a drainage system.

The true toxicity impact of leaked R134a, therefore, is highly uncertain, and unlikely to be as significant as Figure 10 appears to indicate.

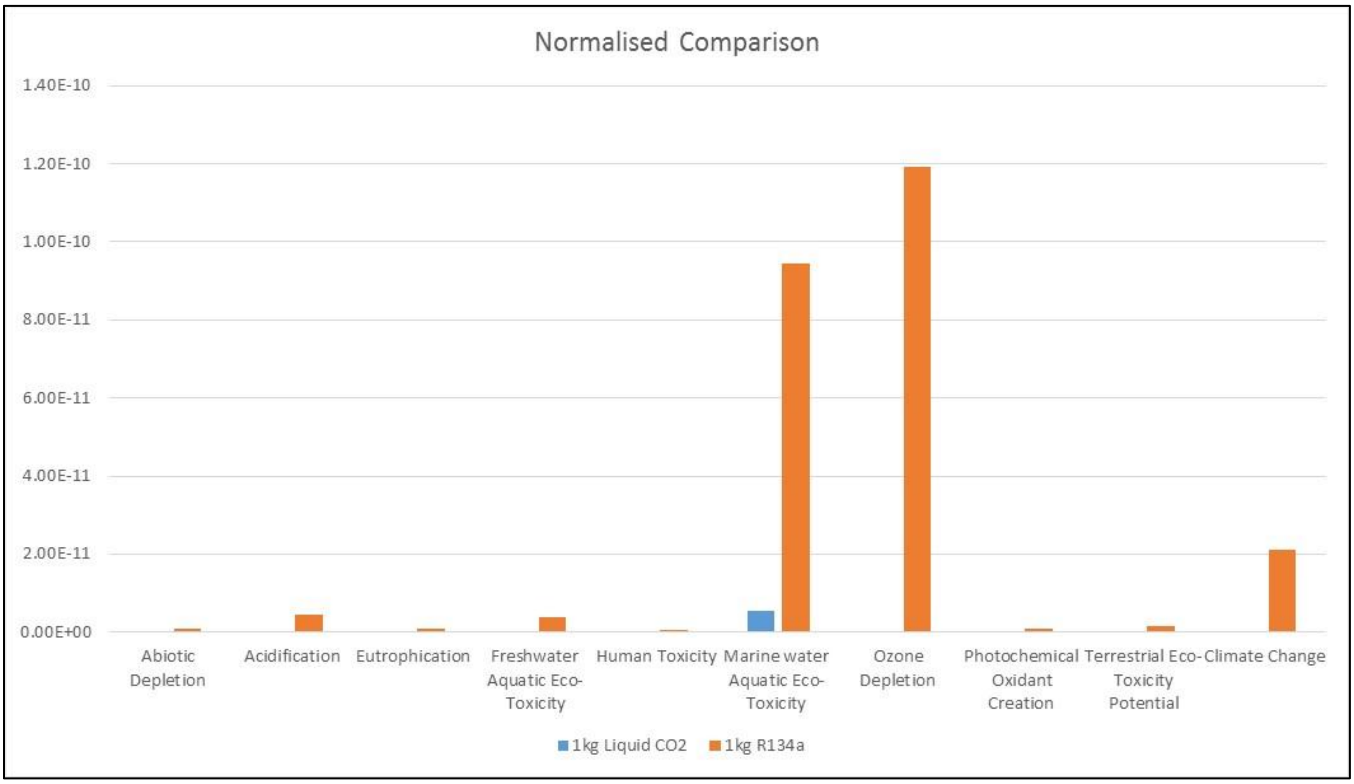

Figure 10: Relative Non-CO_2e Impact of Refrigerants

9.0 Modelling Results

The modelling of deployment to 2020/21 has been conducted in detail with additional higher-level modelling of subsequent deployment to 2050/51. The results are presented in two sections; Section 9.1 addresses CO_2e impacts through to 2020/21 (with related sensitivity analysis in Section 9.2) and Section 9.3 addresses impacts through to 2050/51 (with related sensitivity analysis in Section 9.4). Results are presented both excluding and including AAHPs. The reason for presenting these two cases is because there is significant uncertainty as to the scale of the AAHP market, albeit under most estimates, they account for the majority of the market and therefore have a very significant impact on all results. By removing AAHPs from the analysis it is therefore possible to explore the more detailed changes associated with the other types of heat pump. In this section, wherever the results in both cases are broadly the same, only the charts excluding AAHPs have been used for simplicity.

9.1 CO_2e Impacts to 2020

Drawing upon the deployment figures in Sections 8.1 and 8.2 it is possible to determine the quantity of each type of refrigerant installed in heat pumps through to 2020/21, as shown in Figure 11 (which excludes AAHPs). This analysis shows that almost 2,000 tonnes of refrigerant, including over 1,200 tonnes of R410A, will be in use in heat pumps in the UK in 2020. These figures are utilised as the basis of determining the quantity and type of refrigerant lost in each year, as described below. If AAHPs are included in the analysis, the total deployment of refrigerant reaches 6,000 tonnes, although the overall pattern is very similar.

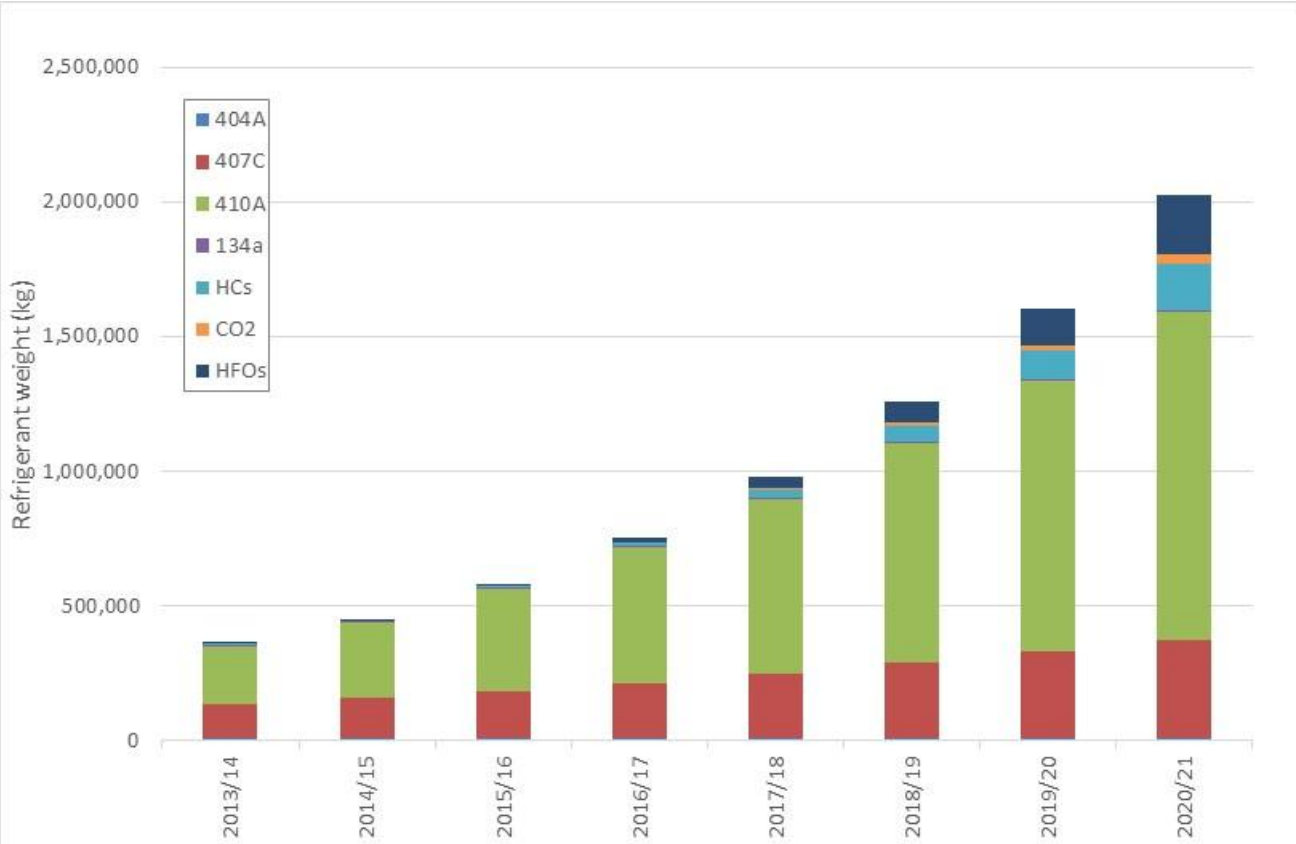

Figure 11: Projected Refrigerant Deployment to 2020/21 (excluding AAHPs)

9.1.1 Modelled Refrigerant Leakage

As described in Sections 5.0 and 6.0, refrigerant leakage was modelled separately for operational emissions and those associated with the broader supply chain (with manufacturing emissions and those from decommissioning contributing the greatest share). The loss of refrigerants from operational leakage is shown in Figure 12 (excluding AAHPs). This table shows an increasing overall refrigerant loss by weight from 13 tonnes in 2013 to 72 tonnes in 2020. This is strongly driven by the increase in heat pump deployment (as is explored further in the sensitivity analysis in Section 9.4.1). Of the refrigerants, R410a contributes over half the losses in each year, and this remains proportionally similar throughout the period to 2020/21. This reflects its' prevalence in the market during this period. Operational leakage as a percentage of total leakage over this period remains largely constant at c.84%. This proportion rises very slightly during this period, reflecting the expected improvements at end-of life.

The results of the analysis of the total losses are very similar to those for operational leakage as shown in Figure 13 with regards to refrigerant split. The major difference is that total leakage reaches c. 82 tonnes by 2020/21.

This analysis indicates that the vast majority of the impact of refrigerants in heat pumps comes from the ongoing leakage, rather than losses associated with other life-cycle (or supply chain) stages. This implies that a reduction in operational leakage rates would have the largest impact on refrigerant loss, despite the relatively high rate of loss due to end of life decommissioning. It is clear, therefore, that improvement of leak detection would have a significant impact on the overall loss of refrigerants from heat pumps.

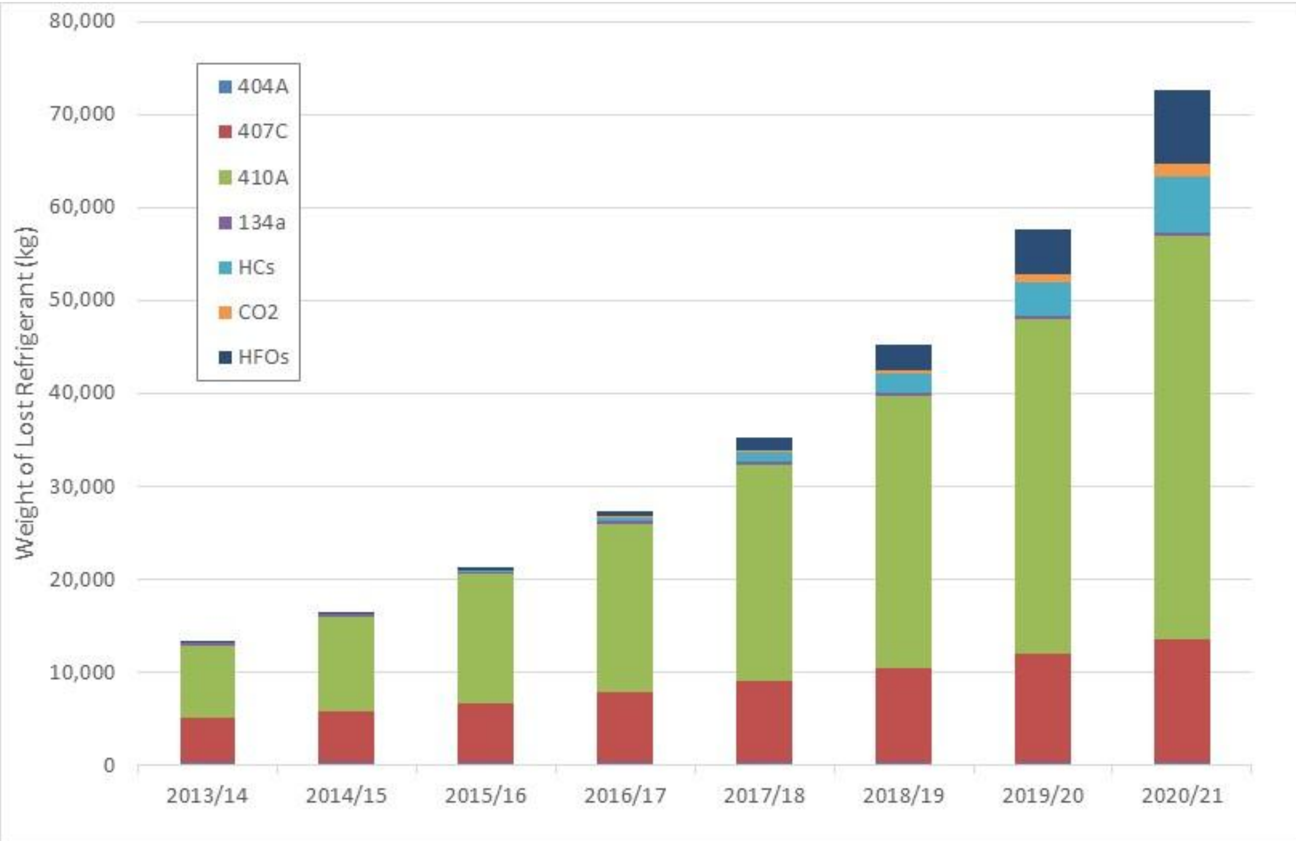

Figure 12: Operational Refrigerant Leakage to 2020/21 (excluding AAHPs)

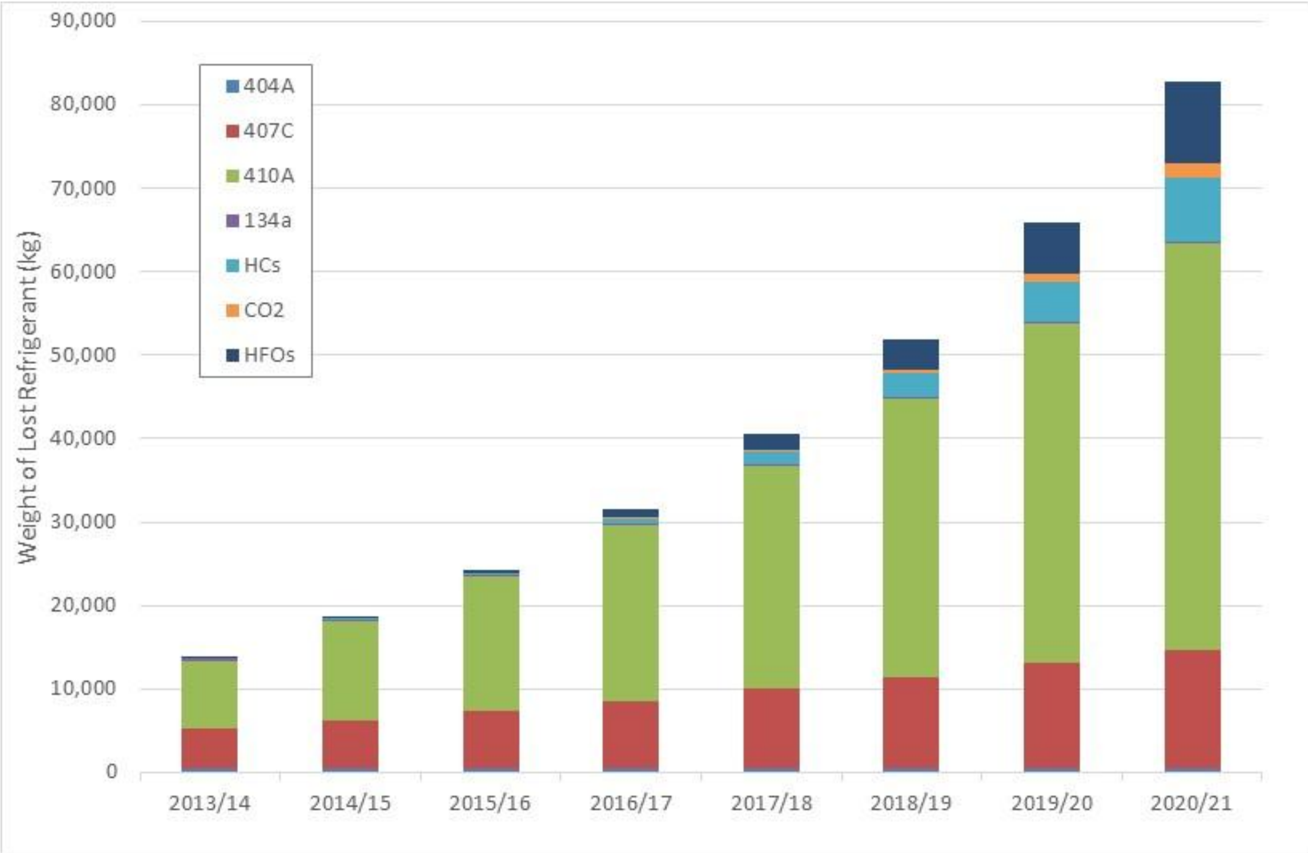

Figure 13: Total Refrigerant Leakage to 2020/21 (excluding AAHPs)

Whilst the total number of heat pumps modelled during this period increases by almost ten-fold, the total refrigerant installed increases by only around half this amount. This reflects the increasing roll-out of domestic installations which have much lower refrigerant charge, and therefore will leak less refrigerant when they do leak. This is due primarily to assumptions relating to the impact of the domestic RHI which commences in spring 2014. This effect is hidden when AAHPs are included as they are such a large proportion of the market that growth in leakage broadly matches growth in these units. When AAHPs are included in the analysis the loss of refrigerants rises to over 200 tonnes by 2020/21 representing the significant size of the AAHP market.

Figure 12 and Figure 13 also show a small, but noticeable shift away from HFC refrigerants towards natural refrigerants and HFOs. This is also clear in the results for the total leakage (including lifecycle and supply chain elements).

9.1.2 Modelled Net Benefits of Heat Pump Deployment

Determining the net CO_2e benefits of heat pumps is a three stage process, which can be summarised as follows:

1. The leakage of refrigerants is converted to CO_2e (which represents the ‘cost’);
2. The CO_2e reduction achieved by displacing counterfactual technologies (for example oil and gas boilers) is determined net of the CO_2e emissions from electricity use (which represents the ‘benefit’); and
3. The cost is subtracted from the benefit.

Each of these three stages are explored below.

CO_2e 'Costs'

The leakage figures derived in Section 9.1.1 can be used to determine CO_2e impacts by utilising the GWP figures for each refrigerant. The results of this analysis are shown in Figure 14 (excluding AAHPs) and Figure 15 (including AAHPs). It is clear that the impact of leakage increases sharply over the course of the seven years, although more notably when AAHPs are removed from the calculations. This reflects the acceleration in deployment due to the RHI. Including AAHPs there is an increase from 200 kilotonnes per annum (ktpa) to 430 ktpa by 2020/21. This is in response to both the significant increase in number of pumps, and the associated greater use of HFCs with high GWPs. This is shown by the vast majority of CO_2e emissions in both Figure 14 and Figure 15 due to R410A and R407C. Indeed, despite a reasonable number of HC and HFO installations in 2020/21, these contribute a minimal proportion of the total CO_2e impact, reflecting their low GWP figures.

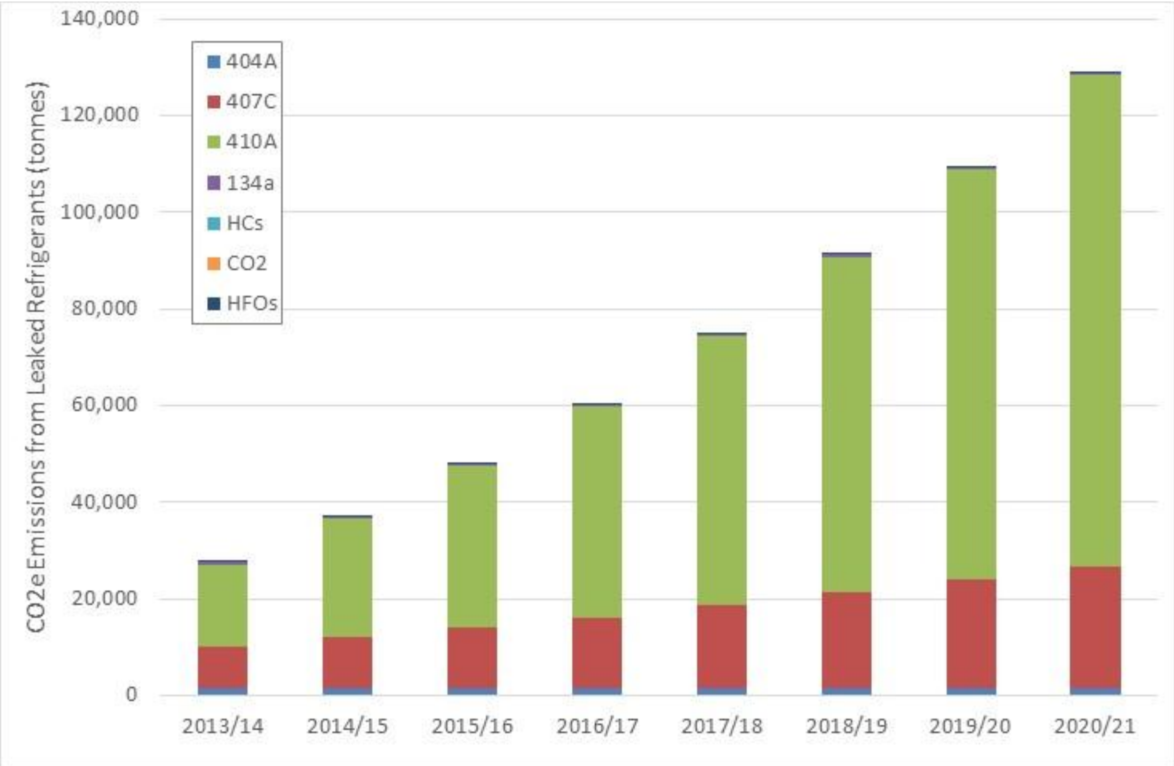

Figure 14: CO_2e Emissions due to Refrigerant Leakage (tonnes) (excluding AAHPs)

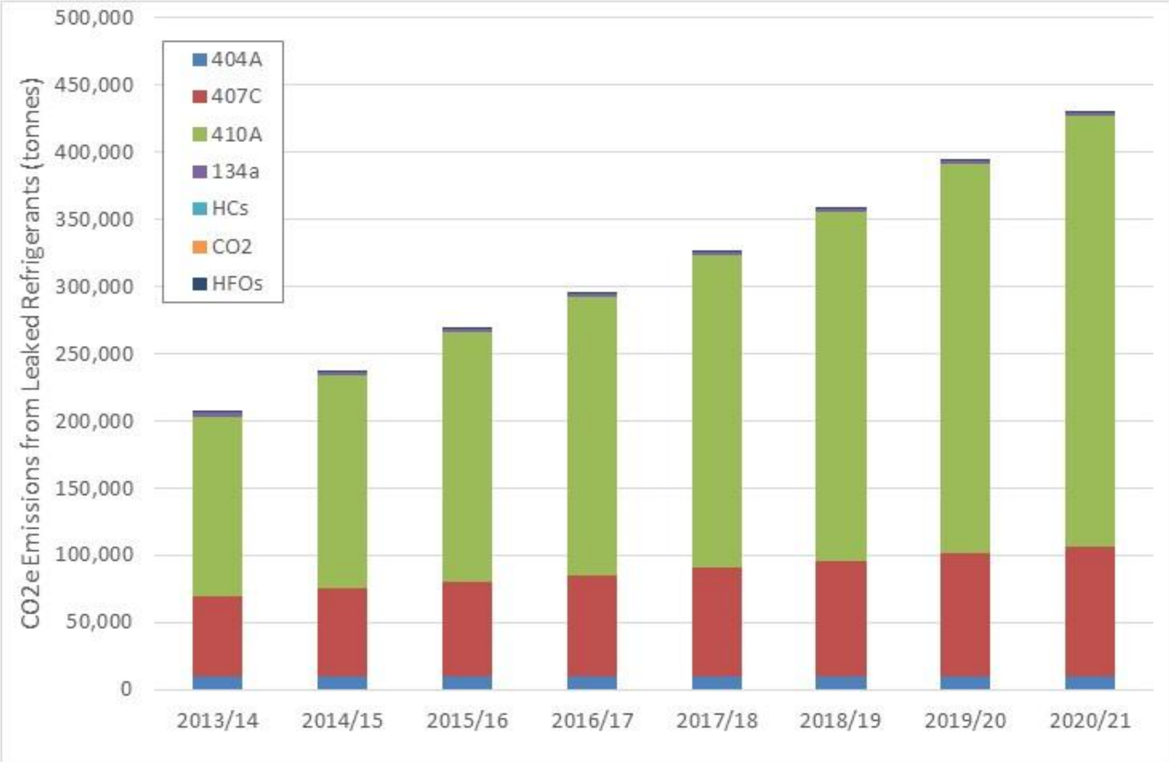

Figure 15: CO_2e Emissions due to Refrigerant Leakage (tonnes) (including AAHPs)

CO_2e Benefits and Net Benefit

As mentioned above, the deployment of greater amounts of heat pumps provides benefits in terms of their replacement of existing fossil fuel heating technologies. As described in Section 8.3, this benefit is determined by calculating the reduction in CO_2e emissions compared to these counterfactual technologies whilst taking into account the CO_2e emissions associated with the electricity used by the heat pumps. The results of this analysis are presented in Figure 16 and Figure 17, excluding and including AAHPs respectively. Both show that the level of benefit is an order of magnitude greater than the emissions associated with refrigerant loss.

Figure 16 and Figure 17 both show that there is likely to be significant growth in net benefit over the period to 2020/21. Assessing the benefits including AAHPs yields a net benefit of around 1.5 million tonnes in 2013/14. By 2020/21 a net benefit of 5.9 million tonnes is projected, indicating a four-fold increase. This net benefit is broadly equivalent to the total emissions from generating electricity via three combined cycle gas turbine (CCGT) plants.[63] Even when AAHPs are removed from the analysis, the net benefits rise from around 0.35 million tonnes to 2.1 million tonnes over the same period. Once more the net benefits by 2020/21 are equivalent to the emissions of a CCGT plant. This analysis clearly suggests that the projected increased roll-out of heat pumps is beneficial in reducing CO_2e impacts through the displacement of more carbon intense technologies despite the associated rise in emissions due to refrigerant losses. If losses could be reduced through early leak detection this net benefit would grow further.

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[63] Based on a carbon intensity of 350kgCO2/MWh for a 1000MW output CCGT plant, which is operating for 5,000 hours per annum (which is reasonable in the current operating environment)

Figure 16: Relative Costs and Benefits due to Heat Pump Operation (excluding AAHPs)

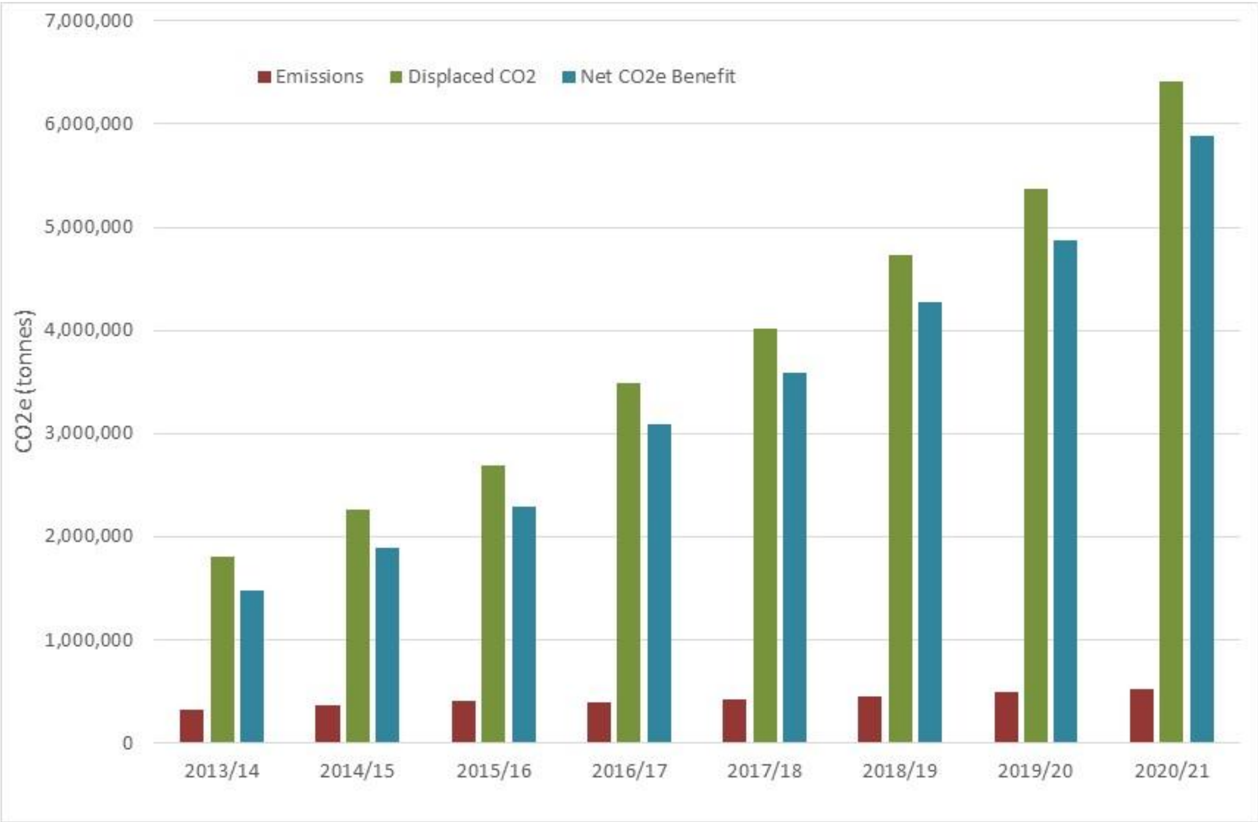

Figure 17: Relative Costs and Benefits due to Heat Pump Operation (including AAHPs)

Both Figure 16 and Figure 17 also show a reduction in costs as a proportion of benefits, which is summarised in Table 25.

Scenario	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21
Excluding AAHPs	7.32%	7.72%	7.92%	7.22%	7.10%	6.75%	6.49%	5.88%
Including AAHPs	11.43%	10.45%	9.98%	8.45%	8.10%	7.58%	7.35%	6.70%

Table 25: Proportion of CO_2e Emission 'Costs' as a Percentage of 'Benefits'

9.2 Results from Sensitivity Analysis to 2020

As highlighted in Section 8.0, a number of sensitivities, in terms of high and low scenarios around key variables, were investigated during the modelling. The impact of each of these is outlined in Sections 9.2.1 to 9.2.5. The results of testing the sensitivity of the central scenario to these variations are presented only for the analysis excluding AAHPs. This is due the very similar nature of the results.

9.2.1 Level of Heat Pump Deployment

The number of heat pumps in operation will clearly drive the quantity of refrigerant being lost from heat pumps and so refrigerant loss is likely to be most sensitive to this variable. As described in Section 8.1, our analysis splits the heat pump market in terms of heat pumps eligible for the RHI, and those which are not eligible. For RHI eligible pumps, projections regarding low, central and high deployment up to 2020/21 exist within DECC's published IAs relating to both the domestic and non-domestic RHI.[64] [65] By contrast no such projections currently exist for the non-RHI market, and thus we have modelled deployment based on separate assumptions, which are described in Section 8.1.

The results from this sensitivity analysis are presented in Figure 18. These show that net emissions are very sensitive to this variable, particularly between the central and high scenarios. The range of potential net-benefits varies from 1.5 million tonnes to around 3.3 million tonnes. This indicates that the actual benefits will vary greatly according to the level of deployment, which suggests that the success of the RHI will be critical to delivering the potential CO_2e savings associated with wide-scale heat pump roll-out.

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[64] DECC (2013) *Impact Assessment: RHI Tariff Review, Scheme Extensions and Budget Management*, September 2013, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/263582/Impact_Assessment_RHI_Tariff_Review_Extensions_and_Budget_Management_Dec_2013.pdf

[65] DECC (2012) *Impact Assessment: Changes to the Current Non-Domestic Renewable Heat Incentive Scheme*, September 2012, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/66606/6444-impact-assessment-on-changes-to-the-current-nondo.pdf

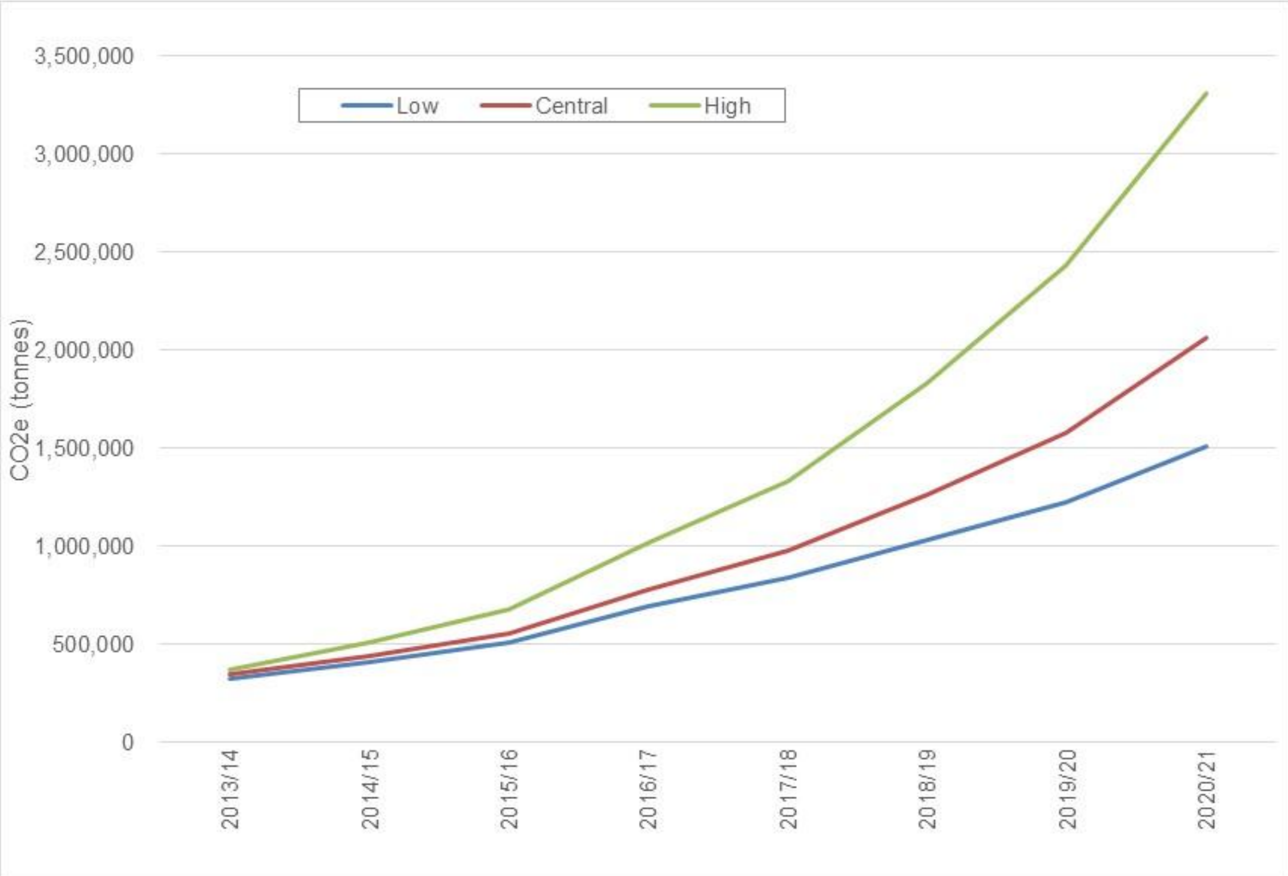

Figure 18: Annual Net Benefit Variation by Deployment Scenario (tonnes CO_2e)

9.2.2 Leakage Rate

The leakage rates associated with heat pumps have a direct impact on the total level of refrigerant lost. As described in detail in Section 5.0 and 6.0, lower levels of leakage might be achieved via:

- Improved design of heat pump units;
- Improved control of lifecycle stages such as manufacture and end-of-life; and
- Improved leakage detection, preventing small leaks becoming larger.

Again, as described in Section 8.2, we have used assumptions for low and high scenarios to test the sensitivity of the central results to this variable. The results of this sensitivity analysis are shown in Figure 19. In both it should be noted that the 'low' scenario relates to low leakage, and therefore results in a higher net benefit. The level of sensitivity over the period to 2020 is notable, as shown in Figure 19. The range of net benefits in 2020/21 is between 1.8 and 2.2 million tonnes. Whilst lower than the range associated with the deployment sensitivity described above, this analysis suggests that a reduction in leakage rates could have act as an important influence towards increasing the net CO_2e benefits associated with heat pumps in the period to 2020/21.

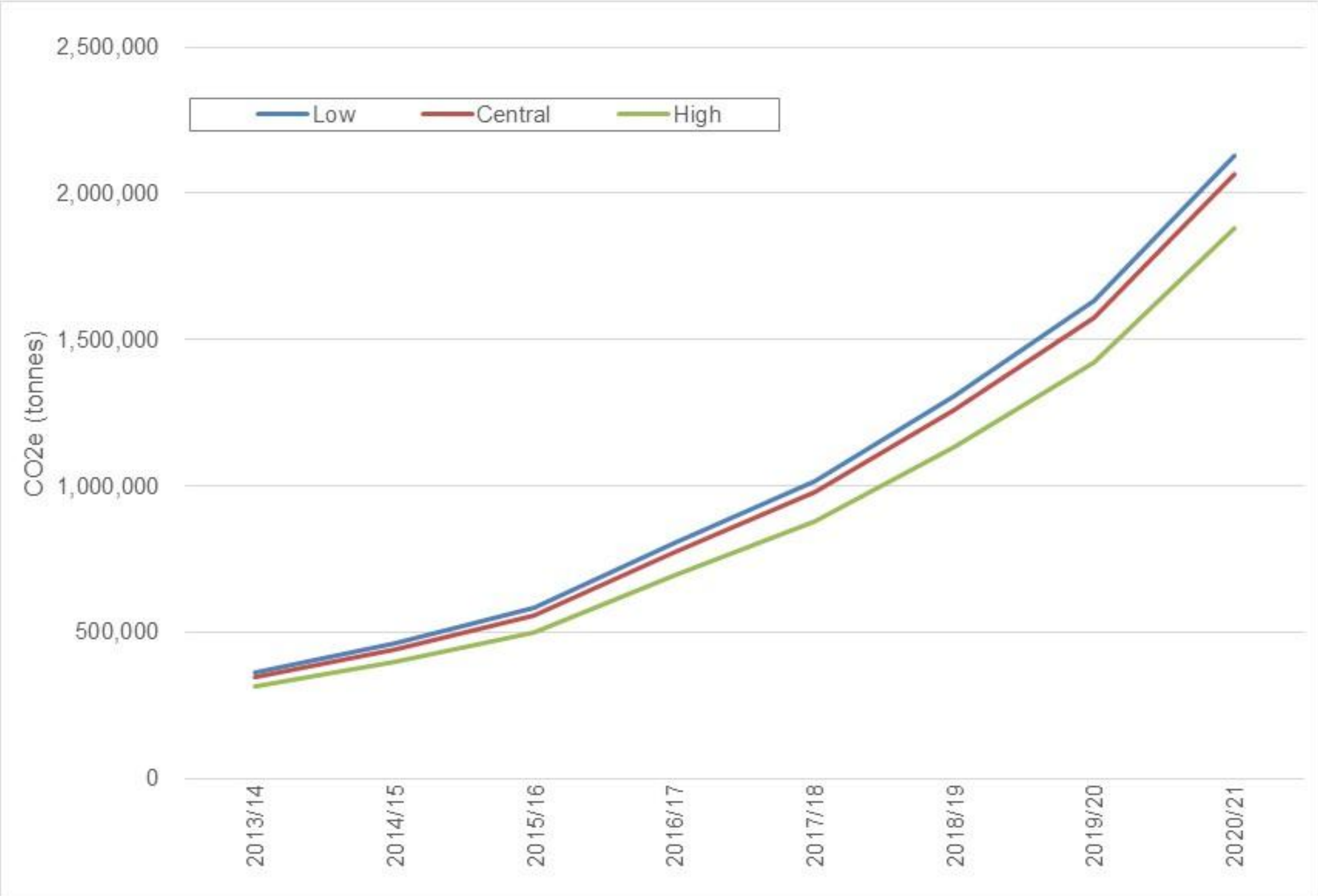

Figure 19: Annual Net Benefit Variation by Leakage (tonnes CO_2e)

9.2.3 Variation in Refrigerant Usage

As discussed in detail in Section 1.0, the intention of the EU F-gas regulations is to shift use of refrigerants away from high-GWP HFCs towards low GWP alternatives. Our assumptions relating to this shift are described in Section 8.2.2, in which we have also set out assumptions relating to a change in the relative balance between new refrigerants such as HFOs and so-called 'natural' refrigerants.

We have deliberately not presented the results from this analysis here, as there is very little change resulting from either of these variables before 2020. In particular, the proportion of natural refrigerants compared to HFOs has almost no impact on the outcome. This is because the likely impact of the F-Gas Regulations will not be fully felt until beyond 2020. Sensitivity analysis for the period to 2050, as explored in Section 9.4, is therefore critical towards testing the impact of this variable.

9.2.4 Variation in SPF

The impact of SPF variation was also explored, and over the period to 2020/21 it was clear that the impact of SPF on net benefits was relatively small, although as shown in Figure 20, it is of a similar magnitude to the impact of changes to the assumed leakage rate. The variation increases as deployment increases and shows that the effect will be multiplied with increasing deployment.

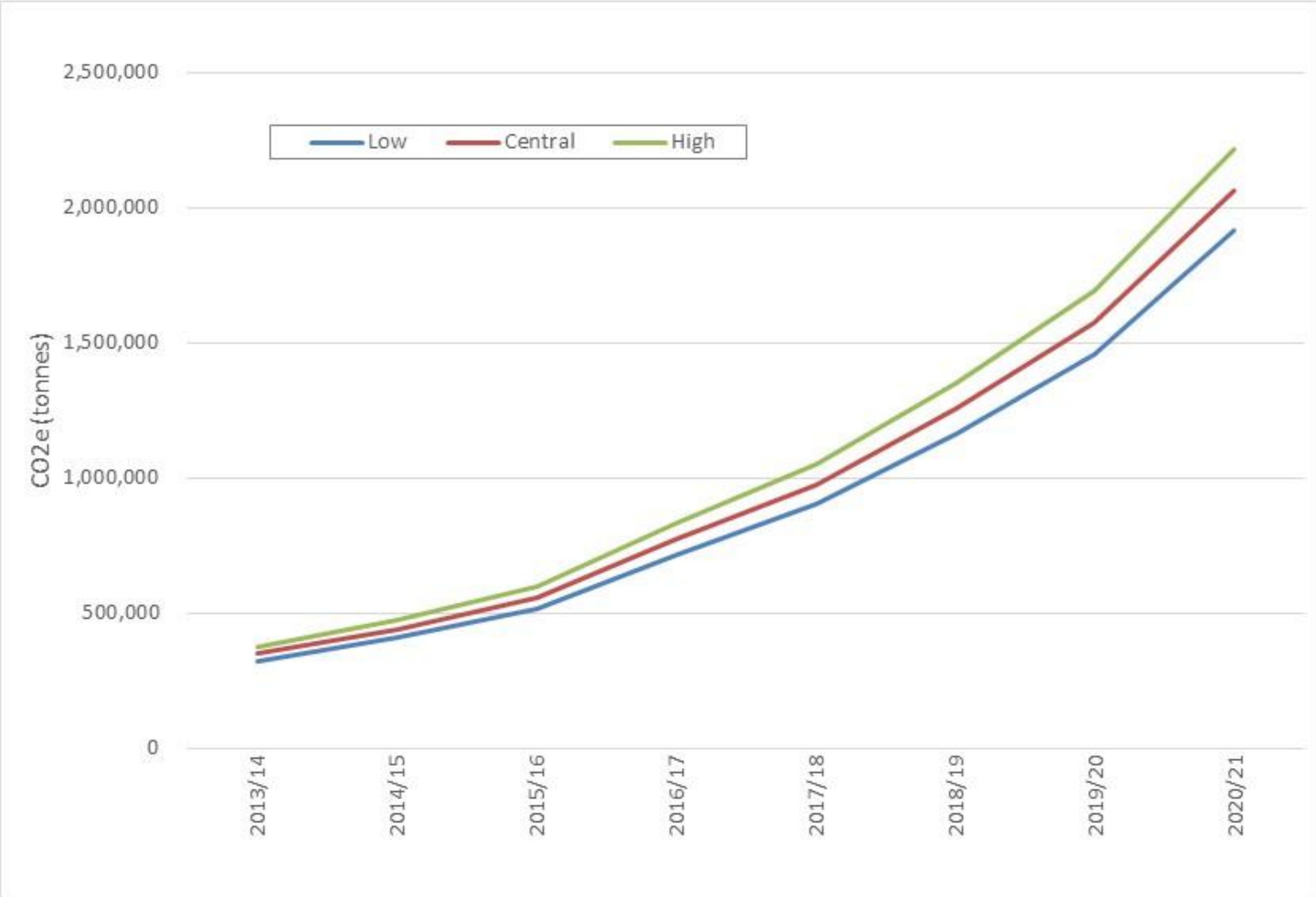

Figure 20: Annual Net Benefit Variation by SPF (tonnes CO_2e)

9.2.5 Analysis of Relative Impact of Sensitivities Tested

There is a clear hierarchy of influence among the variables modelled, with net CO_2e benefit being most sensitive to the level of heat pump deployment. This is unsurprising and indicates that if the RHI (and other policy mechanisms) can effectively incentivise significant uptake of heat pump installations, this will lead to significant carbon savings. Leakage rates, however, also have a reasonable impact on net benefit, which is similar to the impact of variations in SPF, but to a much lesser degree than do variations in deployment levels. Finally, as described above, in the period to 2020, variations in the mix of refrigerants deployed in heat pumps led to almost no impact on net CO_2e benefit.

9.3 CO_2e Impacts to 2050

The same approach to determining CO_2e impacts and benefits that was utilised for the period to 2020/21 has been used for the period to 2050/51. In the following sections, discussion of the process used is therefore not repeated from Section 9.1, instead the focus is on highlighting key findings from the data.

The installed level of refrigerants in heat pump systems over this period is summarised in Figure 21. This indicates that the level of R410A declines from being the dominant refrigerant to being a small fraction of installed capacity by 2050/51, reflecting the reductions in use of HFCs in general. At the same time the overall level of refrigerants deployed grows three-fold, reflecting the continuing growth in deployment of heat pumps through this period.

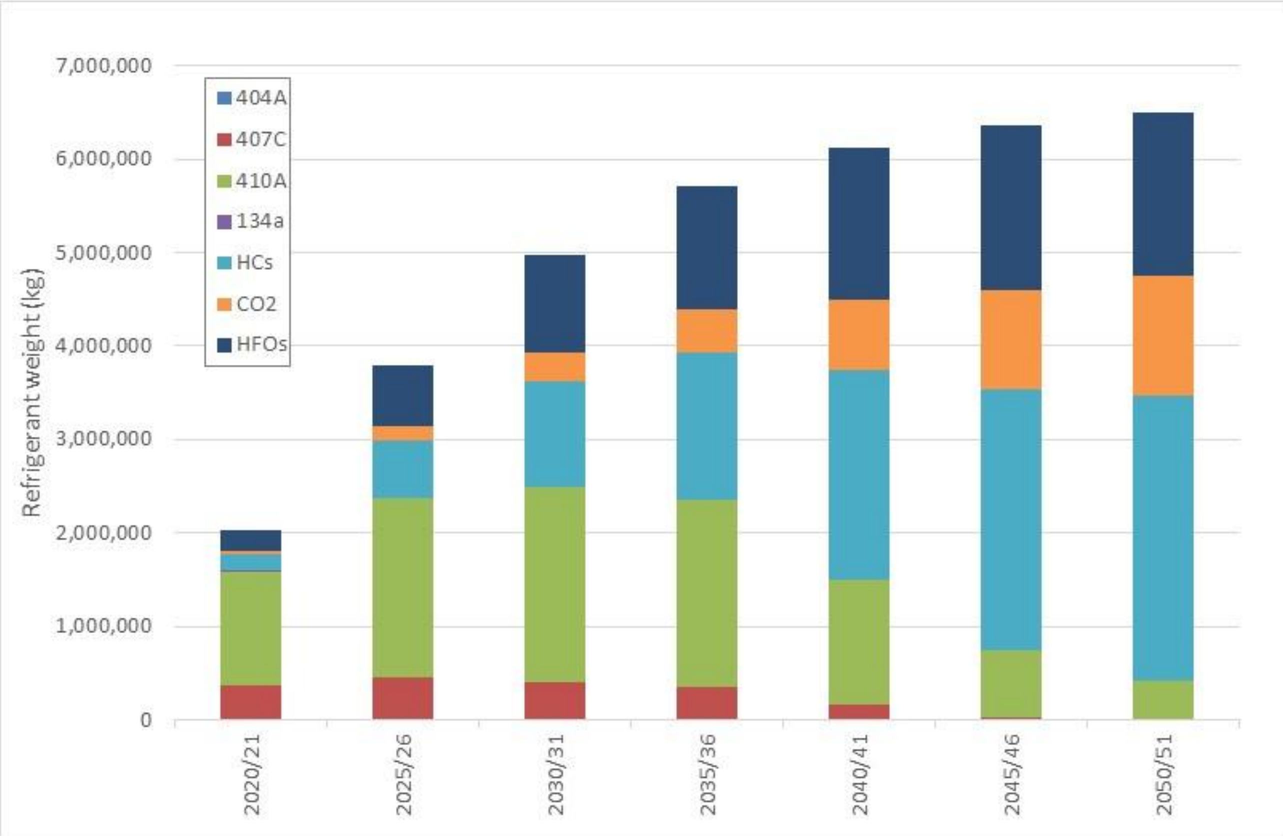

Figure 21: Refrigerant Contained within Heat Pumps to 2050/51 (excluding AAHPs)

9.3.1 Modelled Refrigerant Leakage

As with the leakage modelled up to 2020/21, operational and supply chain leakage were modelled separately. The loss of refrigerants from operational leakage is shown in Figure 22 which indicates a significant growth in losses from natural refrigerants and HFOs, reflecting the growth in deployment of these refrigerants, as discussed above. As for the period to 2020/21, operational leakage represents the majority of quantifiable refrigerant loss. The overall losses are shown in Figure 23.

Figure 22: Operational Refrigerant Leakage to 2050/51 (kg) (excluding AAHPs)

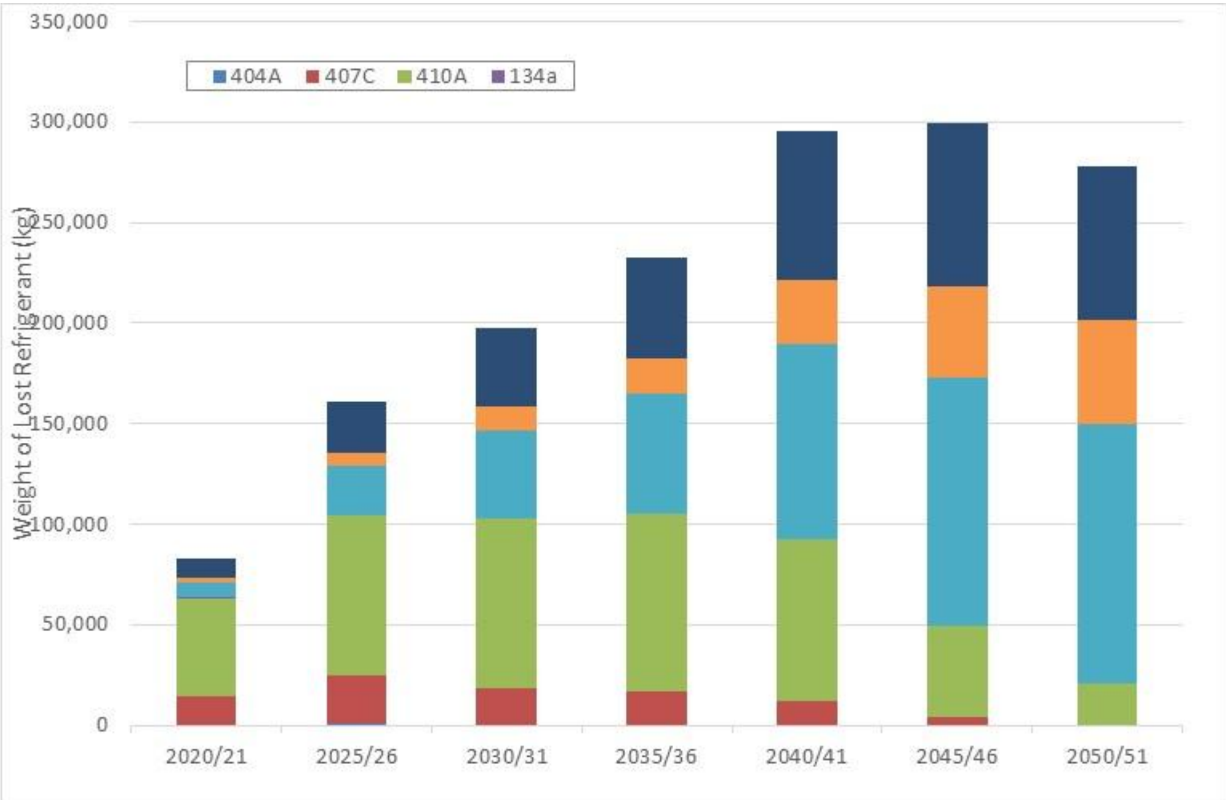

Figure 23: Total Refrigerant Leakage to 2050/51 (kg) (excluding AAHPs)

9.3.2 Modelled Impact of Refrigerant Leakage

Figure 24 shows that the impact of leakage of refrigerants from heat pumps follows a pattern of growth and then decline over the period to 2050. This reflects the effect of two factors:

- The continuing increase in the number of heat pumps installed, which increases the quantity of refrigerant lost; and
- The shift from HFCs to low GWP refrigerants, which reduces the CO2e impact (per tonne of refrigerant) when leakage takes place.

As can be seen, the impact of refrigerant leakage in 2050 is under half that in 2020 and less than a quarter of the impact during the period 2025-2035. This indicates how significant the benefit is of reducing the use of HFCs. This decline also occurs despite the significant additional deployment of heat pumps during the interim period.

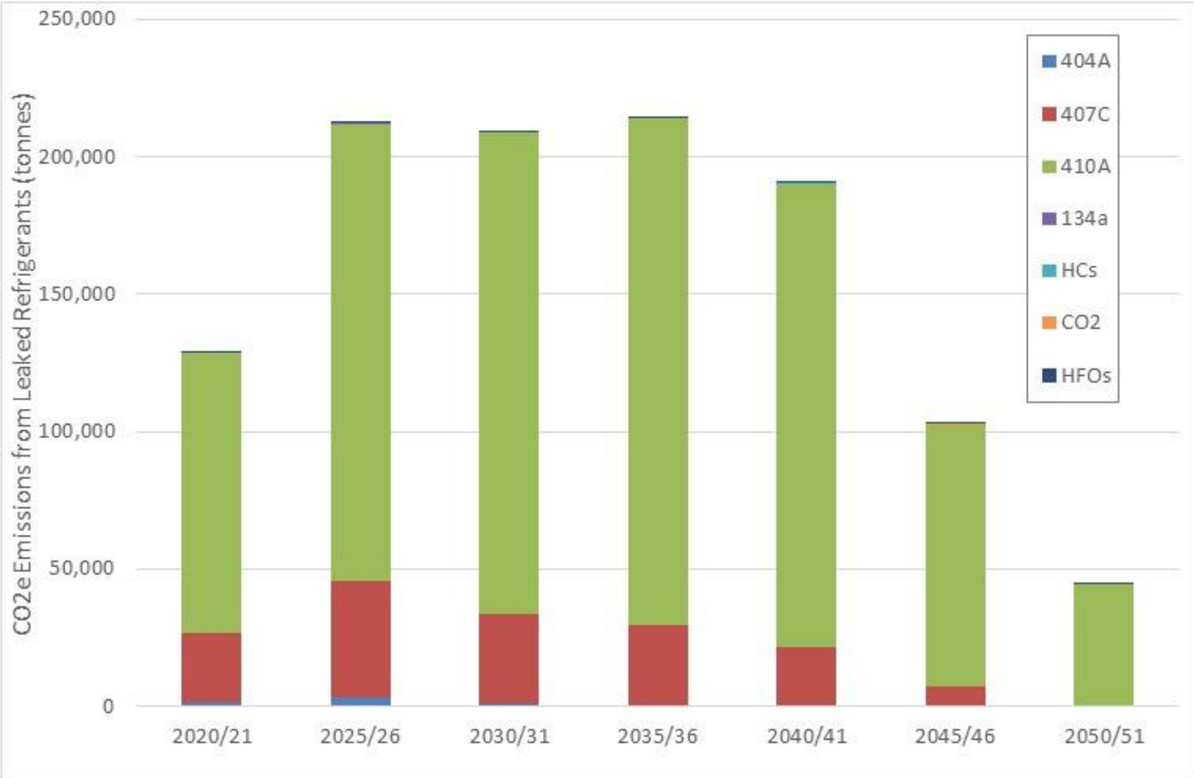

Figure 24: CO_2e Emissions due to Refrigerant Leakage to 2050/51 (tonnes) (excluding AAHPs)

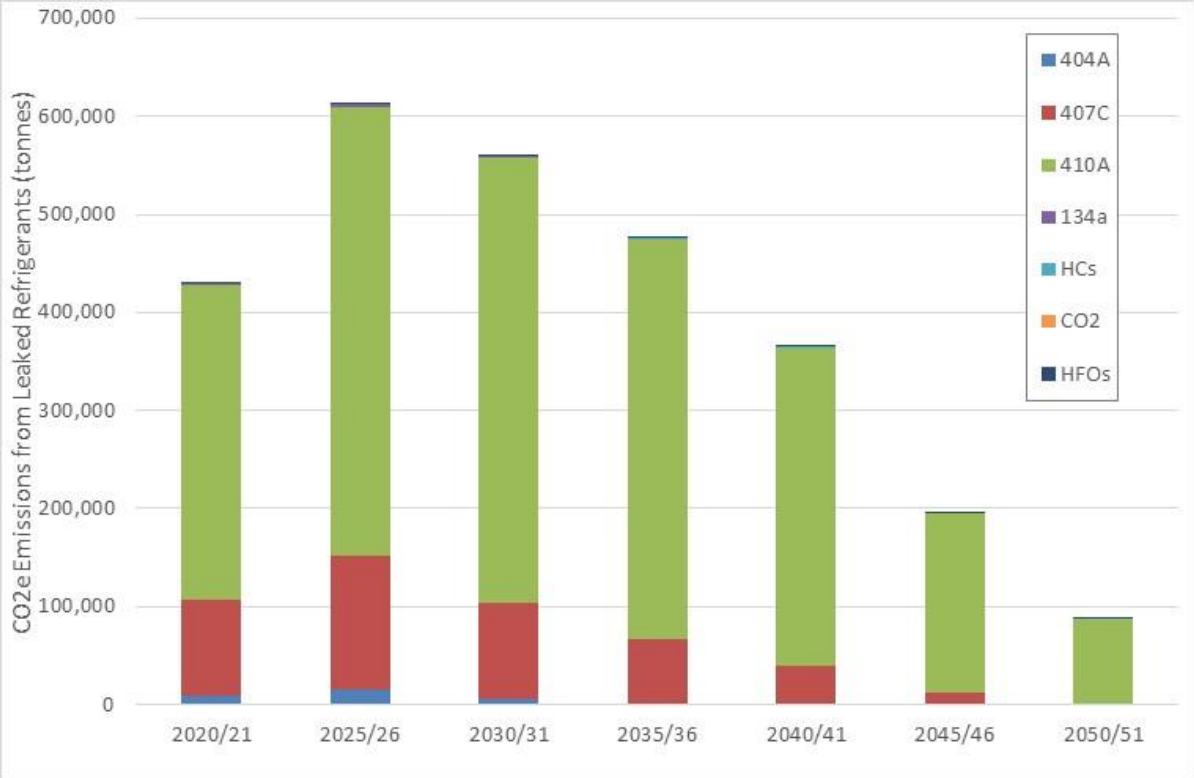

Figure 25: CO_2e Emissions due to Refrigerant Leakage to 2050/51 (tonnes) (including AAHPs)

9.3.3 Modelled Net Benefits of Heat Pump Deployment

As per the approach described above for the analysis to 2020/21, the benefits and net benefits have been modelled to 2050/51 and are shown in Figure 26 and Figure 27. These benefits increase substantially over this period due to the increasing deployment of pumps, and the improved efficiency (SPF) of the systems, which means that they require less energy to generate the same amount of heat. Similarly, the decarbonisation of the grid, from which heat pumps draw their electricity supply, further reduces their CO_2e impact, thus increasing the net benefit.

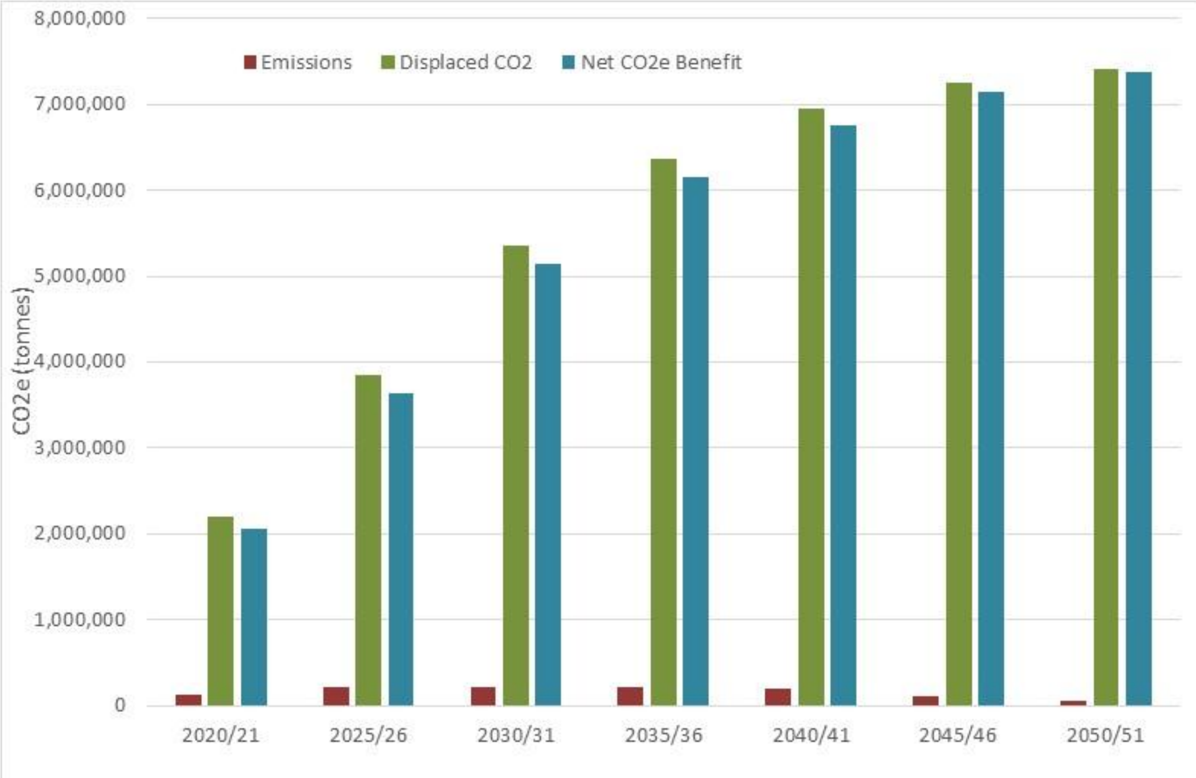

Figure 26: CO_2e Environmental Costs and Benefits of Heat Pumps to 2050/51 (tonnes CO_2e) (excluding AAHPs)

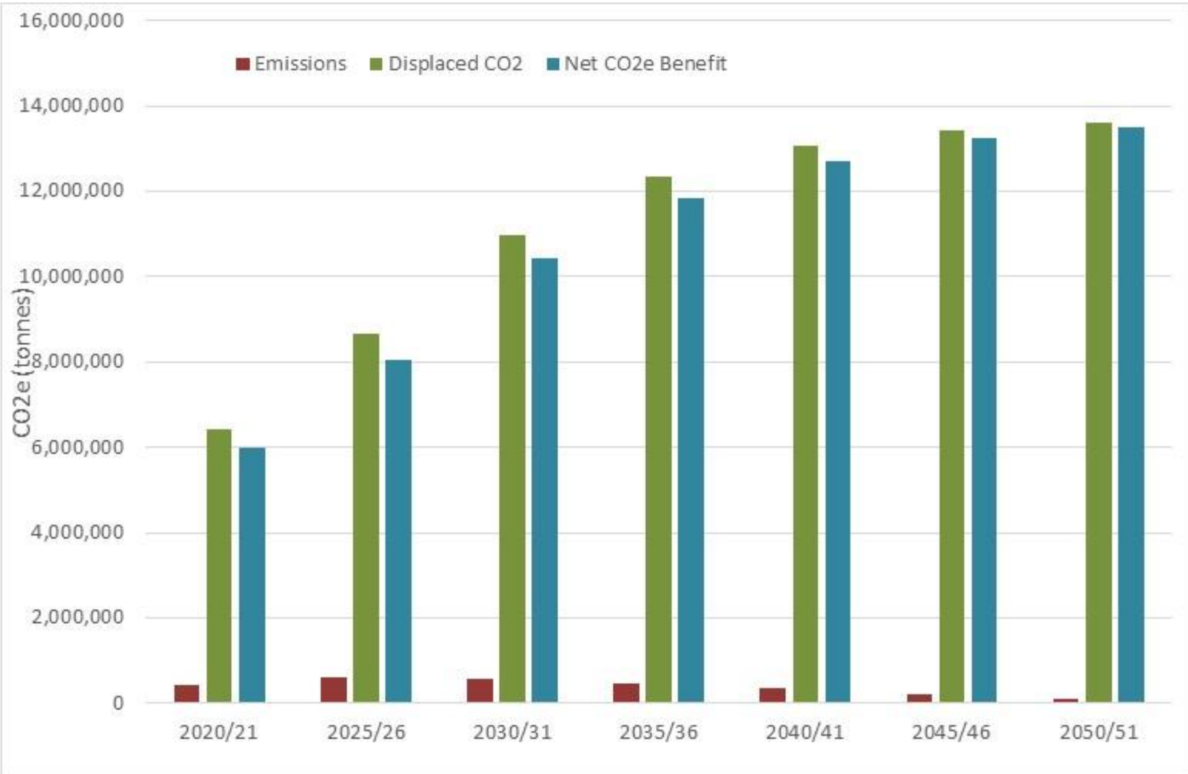

Figure 27: CO_2e Environmental Costs and Benefits of Heat Pumps to 2050/51 (tonnes CO_2e) (including AAHPs)

The net benefit results presented in Figure 26 and Figure 27 reflect the significant decrease in emissions and increase in displaced CO_2e that occurs over this period. As a result, the proportion of emissions to displaced CO_2e declines throughout until it is just above 0.60% by 2050 as indicated in Table 26. This indicates that in the longer term, as the switch is made to lower GWP refrigerants, the marginal benefits of heat pumps increase significantly.

Scenario	2020/21	2025/26	2030/31	2035/36	2040/41	2045/46	2050/51
Excluding AAHPs	5.88%	5.52%	3.91%	3.37%	2.74%	1.42%	0.61%
Including AAHPs	6.70%	7.07%	5.10%	3.86%	2.80%	1.46%	0.65%

Table 26: Proportion of CO_2e Emission 'Costs' as a Percentage of 'Benefits'

The net benefits by 2050/51 are broadly equivalent to the total emissions from generating electricity via more than three CCGT plants (if AAHPs are excluded) and almost seven if they are included.[66] This highlights the very significant benefits potentially associated with heat pump deployment over the longer term. Given the benefits associated with heat pumps utilising low GWP refrigerants and powered by a low carbon grid, it is therefore clearly desirable (in terms of delivering CO_2e savings via changes from heat provision) for increased deployment to occur throughout the UK where there are suitable buildings.

9.4 Results from Sensitivity Analysis to 2050

As discussed in Section 8.0, a number of sensitivities, presented in terms of high and low scenarios around key variables, were investigated via the modelling. The approach to testing the impact of these sensitivities upon the central results was exactly the same as that used for the modelling to 2020/21. The impact of each of these sensitivities is explored in Sections 9.4.1 to 9.4.5. As discussed in Section 9.2, for simplicity, these sensitivities are only presented for the set of results with AAHPs excluded.

9.4.1 Level of Heat Pump Deployment

The results from the sensitivity analysis on the level of deployment are shown in Figure 28.

[66] Based on a carbon intensity of 350kgCO2/MWh for a 1000MW output CCGT plant, which is operating for 5,000 hours per annum (which is reasonable in the current operating environment)

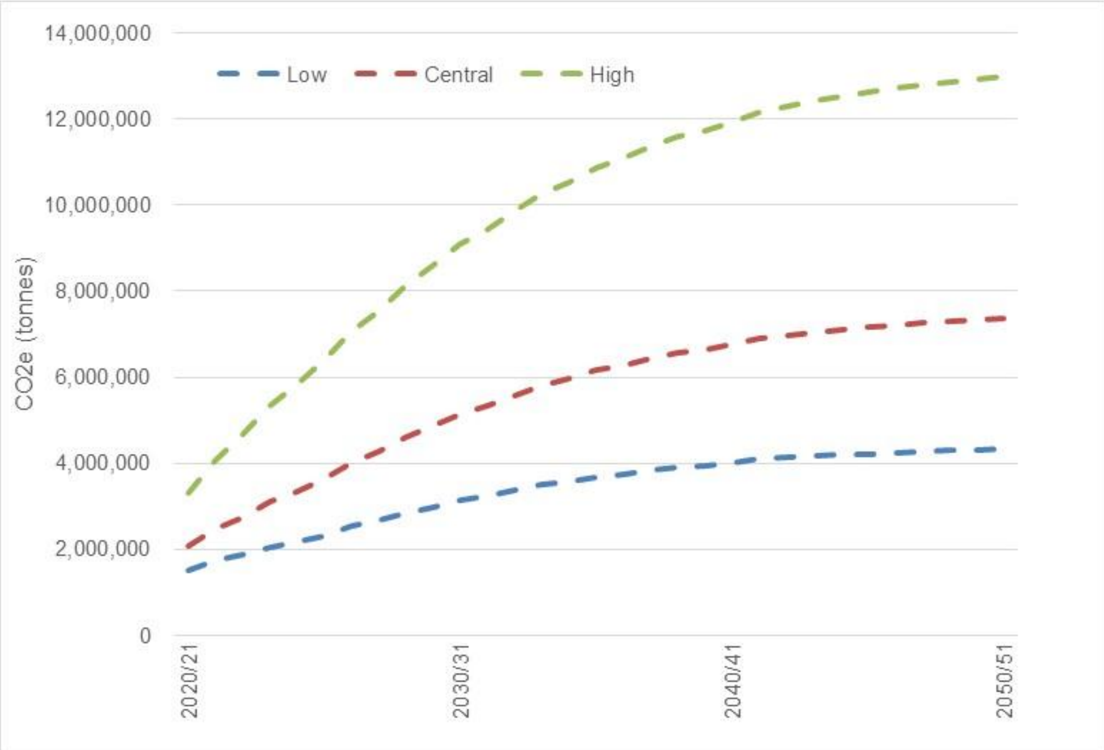

Figure 28: Annual Net Benefit Variation by Deployment Scenario to 2050/51 (tonnes CO_2e)

As with the analysis to 2020/21, the net benefits attributable to heat pumps are extremely sensitive to the level of assumed deployment. In particular the high scenario represents 76% greater benefit than the central scenario, an amount which would be equivalent (in CO_2e emission terms) to a further 2.5 CCGT plants. This clearly illustrates both the sensitivity to deployment, and the potential to deliver significantly greater benefits by driving further heat pump deployment in the UK.

9.4.2 Leakage Rate

As with the analysis to 2020/21, the net benefits are notably sensitive to leakage rate variation. During the period to 2050/51, however, this level of sensitivity decreases markedly, as the GWP of the refrigerants in use reduces. To put this in simple terms, it would take many kilograms of refrigerant leakage in 2050 to have the same impact as 1kg of refrigerant leakage in 2020. Therefore, even though the leakage rates are varied, the impact of this variation declines over time. This is highlighted in Figure 29, which shows that the low leakage scenario delivers an increase in benefits in 2050/51 of less than 1%, whilst the high leakage scenario leads to a reduction in benefit of around 1%. When compared to the analysis over the period to 2020, this indicates that whilst in the short term it is important to reduce leakage wherever possible, in the longer term this is not so critical assuming lower GWP refrigerants are used.

This analysis suggests that (alongside provision of support for increased deployment) trying to reduce leakage in the short-term, whilst incentivising low GWP refrigerants in the longer term would be the most appropriate course of action to maximise the CO_2e benefits associated with heat pumps. It is also notable that the low and high scenarios only converge towards the end of the period to 2050/51. This is largely due to the long time lag before actual deployment of new refrigerants, which reflects the anticipated 20-year lifetime of heat pump installations. If replacement of HFCs with low GWP refrigerants was mandated (under the revised F-Gas Regulations, as discussed in Section 2.2) for all installations (not just new installations) then this convergence would occur sooner, along with overall greater net CO_2e benefits. Such CO2e benefits, however, would come at the cost of retrofitting systems where no ‘drop in’ replacement was available, which could be very substantial, representing a significant cost to industry, at this stage of market development.

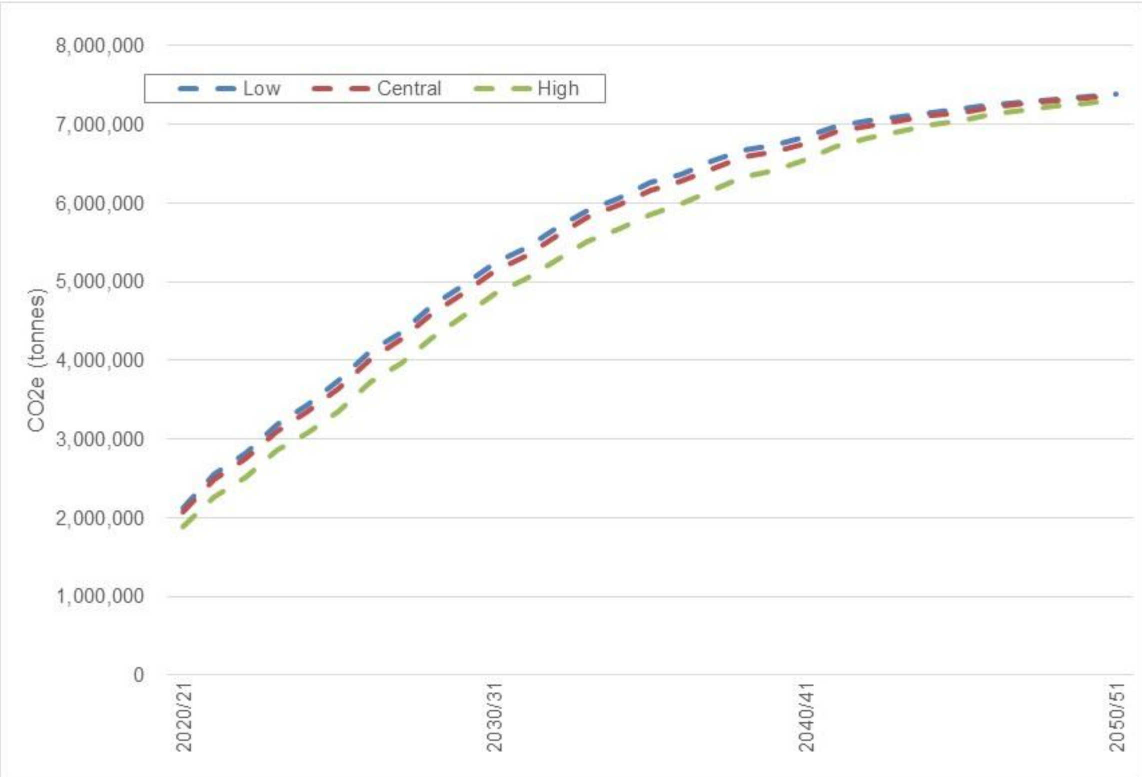

Figure 29: Annual Net Benefit Variation by Leakage Rate Scenario to 2050/51 (tonnes CO_2e)

9.4.3 Variation in Refrigerant Usage

As described in Section 9.2.3 for the period 2020/21, variation in types of refrigerant utilised had minimal impact on net benefits. The modelling to 2050/51 indicates that the impact remains relatively low, but the level of sensitivity of the results to such variation does increase from 2030 onwards due to restrictions on HFCs, as shown in Figure 30.

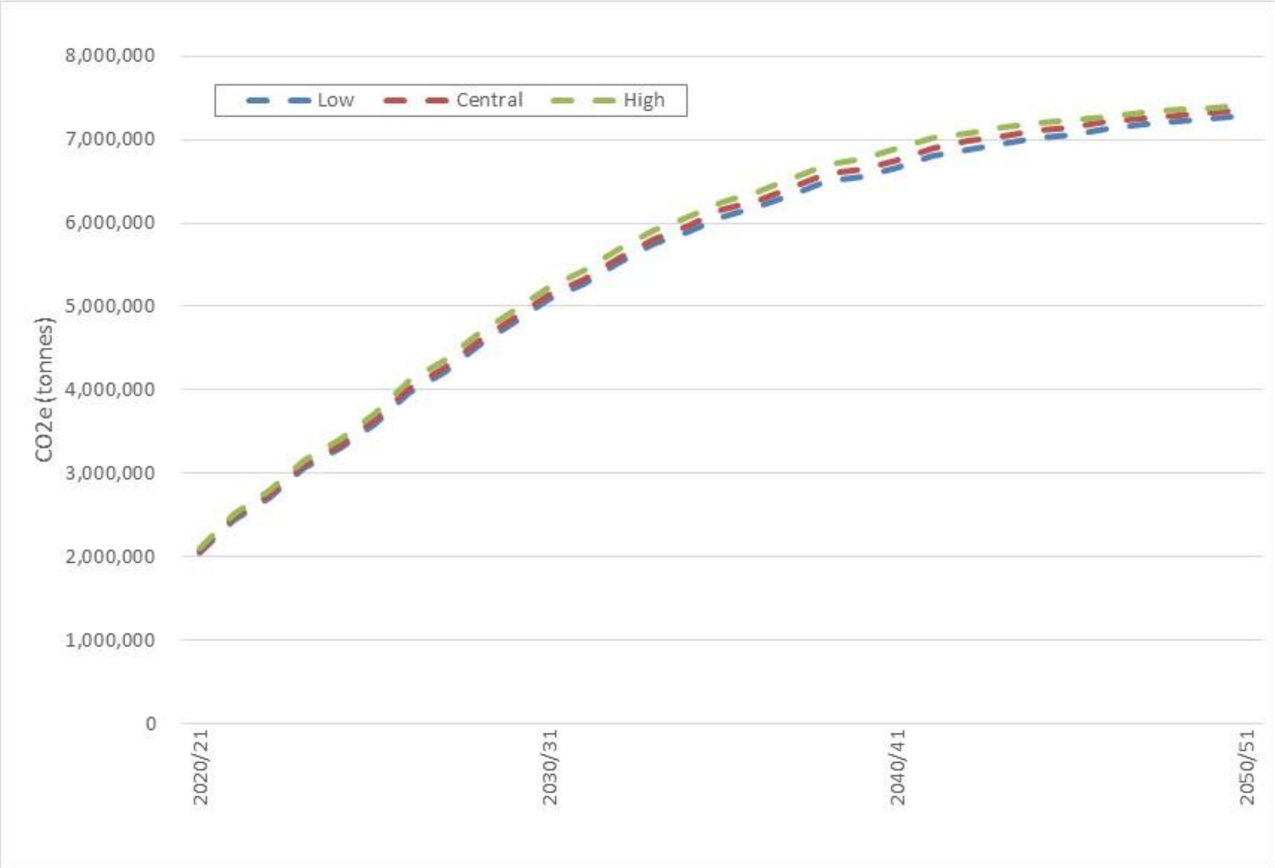

Figure 30: Annual Net Benefit Variation by Restrictions on HFCs Scenario to 2050/51 (tonnes CO_2e)

The increasing variation is again driven in part by the long time lag before actual deployment of the new refrigerant mix, which reflects the anticipated 20-year lifetime of heat pump installations. Nonetheless, by 2050 the level of variation falls as the full impacts of HFC reduction (driven by the F-Gas Regulations, as discussed in Section 2.2) begin to filter through in each scenario. As a result, the low and high scenarios each only represent a 1% deviation from the central scenario in 2050/51.

Our analysis showed that the variation attributable to the balance between HFOs and 'natural' refrigerants remained negligible over this period, primarily due to the similarity in GWP for these refrigerants, and so no results are presented here.

9.4.4 Variation in SPF

The results of the sensitivity analysis for SPF values over the period to 2050/51 are presented in Figure 31. This shows that as deployment increases, the potential impact of variations in the SPF becomes much greater, with a range of c.1 million tonnes CO_2e by 2050/51, which is roughly half the output of a CCGT plant. Whilst in the short term, therefore, the impact of SPF on CO_2e benefits is likely to be small, as deployment increases, so will the benefits from improved SPFs. It should also be noted that a focus on the delivery of high SPFs by manufacturers will also lead to reductions in consumer bills.

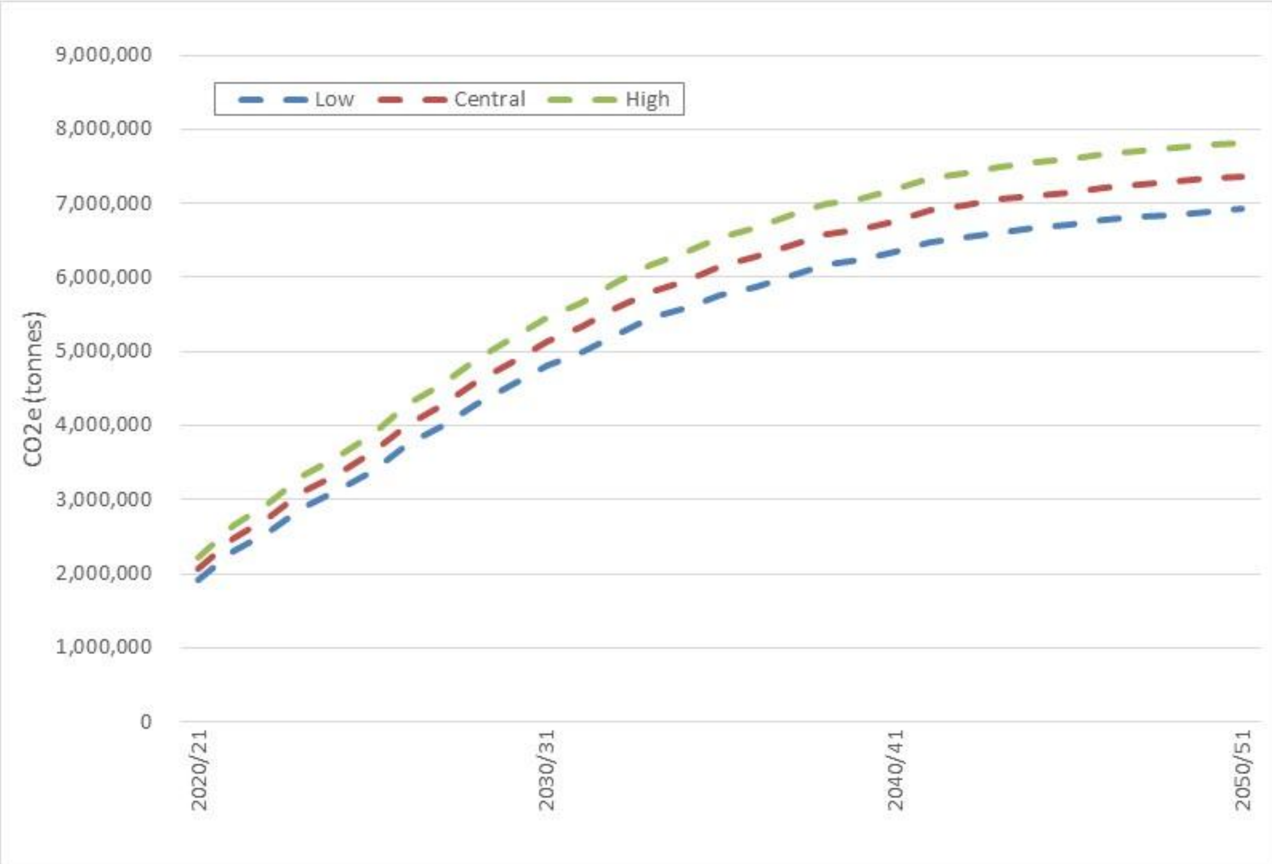

Figure 31: Annual Net Benefit Variation by SPF to 2050/51 (tonnes CO_2e)

9.4.5 Analysis of Relative Impact of Sensitivities Tested

As with the period to 2020/21, net benefit is most sensitive to variations in deployment, indicating that incentivising heat pump uptake can lead to significant CO_2e benefits. In the period to 2050/51, however, the impact of variations to leakage rates diminishes significantly due to the reduction of HFCs. Similarly the impact of restrictions on HFCs (driven by the F-Gas Regulations, has a far more limited impact during this period. In both instances, this is because the resulting changes in mix of refrigerants deployed take time to manifest themselves as CO_2e benefits due to the lag in replacing older systems, which are assumed to continue to use HFCs for the remainder of their 20-year lifetime.

10.0 Conclusions

This report explores the net benefit (expressed in CO_2e terms) of heat pumps in the UK, taking into consideration the emissions associated with refrigerant leakage, the assumptions for which were informed by primary research and a limited amount of practical tests.[67]

The headline findings from the study can be summarised as follows:

- It was determined from analysis of F-gas log books that annual leakage rates from operation of heat pumps were of the order of 3.8% of installation charge for non-domestic applications and 3.5% for domestic applications;
- Analysis of this data suggest that 9% of non-domestic installations and 10% of domestic installations leaked each year;
- There is scope to reduce levels of leakage further, thereby increasing the net benefit associated with heat pumps;
- It was determined that data contained within F-gas log books were generally of poor quality and that the way log books are currently being maintained within the UK represents a significant challenge to undertaking analysis of this nature;
- The emissions associated with refrigerant leakage are calculated to be 128,000 tonnes of CO_2e per annum in 2020/21. In the subsequent period to 2050/51, the emissions associated with leakage fall to 46,000 tonnes CO_2e per annum;
- This significant reduction, which occurs at the same time as increasing levels of heat pump deployment and corresponding rises in the losses of refrigerants, is due to the switch from HFCs (which exhibit high GWP characteristics) to low GWP alternatives, such as ‘natural’ refrigerants and HFOs;
- It is clear, therefore, that switching to low GWP alternative refrigerants within heat pumps will have a very significant impact in reducing emissions;
- The analysis suggests that trying to reduce the level of leakage in the short-term whilst incentivising low GWP refrigerants in the longer term would be the most appropriate course of action to maximise the CO_2e benefits associated with heat pumps;
- The levels of emissions from leakage, however, are small relative to the total emissions reductions which might be delivered by heat pump technologies via the displacement of fossil fuelled heating alternatives. The results of the modelling show that at 2.19 million tonnes CO_2e per annum in 2020, this level of benefit is an order of magnitude greater than the emissions associated with refrigerant loss; and
- The total net benefits, under our central assumptions, of 2.07 million tonnes Co_2e per annum in 2020/21 and of 7.37 million tonnes Co_2e per annum in 2050/51 suggest that it is beneficial (in terms of net CO_2e emissions) to incentivise the further deployment of heat pumps in the UK.

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[67] All quoted figures refer to impacts **excluding** Air to Air Heat Pumps.

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