ICF INTERNATIONAL

DEVELOPMENT OF THE GHG REFRIGERATION AND AIR CONDITIONING MODEL

FINAL REPORT

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By ICF International

Table of Contents

Executive Summary

In an effort to improve the greenhouse gas (GHG) emission estimates for the UK's refrigeration and air conditioning (AC) sector, ICF International reviewed and updated the Department of Energy and Climate Change's (DECC) existing inventory model for 1990-2050. The inventory model is used by DECC to report annual emissions of GHGs, as required under the European Union's (EU) Monitoring Mechanism Decisions (No. 280/2004/EC). In addition to improving the accuracy and transparency of the model, DECC also requested that the model be made more flexible so that it can be used to inform policy and decision-making.

To respond to this request, ICF first examined both the existing structure and organization of the model as well as the quality of the input assumptions to identify strengths, weaknesses, uncertainties, and areas for improvement. Significant areas for improvement included the addition of new end-uses; use of bottom-up data across all end-uses; addition of ozone depleting substances (ODS) and natural refrigerants; incorporation of likely future market conditions pertaining to the transition away from hydroflurocarbons (HFC) refrigerants through to 2050; and enhanced model functionality and transparency. To revise and develop new input assumptions, ICF conducted an extensive literature review and contacted key industry stakeholders. Priority industry stakeholders were selected across all end-uses and initially contacted to fill data gaps and corroborate information found in the literature. Following the development of preliminary assumptions for all end-uses, the draft assumptions were then shared with a broader range of stakeholders to solicit additional industry input and vet assumptions.

The previous version of DECC's model (v8) was organized into nine end-uses, all but two of which were modelled using a top-down approach (based on refrigerant sales data). ICF revised the model to include 13 end-uses to more accurately and transparently reflect the UK market, and developed definitions to clarify the equipment represented by each end-use. The end-uses defined in both the previous and revised model are summarised in the table below.

Table 1. Previous and Revised Model End-Uses

Previous	Revised
Domestic Refrigeration	Domestic Refrigeration
Other Small Hermetic Refrigeration Units	Small Commercial Stand-Alone Refrigeration Units
Small Commercial Distributed Systems	Condensing Units
Supermarket Systems	Centralised Refrigeration Systems
Industrial Systems	Industrial Systems
Building Air-conditioning Systems	Small Stationary Air Conditioning
	Medium Stationary Air Conditioning
	Heat Pumps
Building Air-conditioning Chillers	Large Stationary Air Conditioning (Chillers)
Refrigerated Transport	Land Transport Refrigeration
	Marine Transport Refrigeration
Mobile Air-conditioning	Light Duty Mobile Air Conditioning
	Other Mobile Air Conditioning

For each of the end-uses, detailed assumptions were developed to utilise a bottom-up approach, using market data and other country-specific information to develop assumptions on the number of equipment stocks and average charge size per unit to estimate emissions. Specifically, assumptions regarding the following were developed for each end-use across the 1990-2050 time series:

1. Equipment stocks
2. Market growth
3. Equipment lifetimes
4. Refrigerant market penetrations
5. Charge sizes
6. Manufacturing, operational, and disposal leak rates

Table 2 summarises the 2010 input assumptions developed by end-use.

Table 2. Summary of 2010 Input Assumptions by End-Use

Application		2010 Parameters							
CRF Sector	UK Category	Total Stock (units)[a]	Total Sales (units)[a]	Lifetime (years)	Charge (kg)[a]	Refrigerants in New Equipment	Manufacturing Loss Rate	Operational Loss Rate	Disposal Loss Rate
Domestic Refrigeration	Domestic Refrigeration	40,430,000	2,939,680	15	0.10	HFC-134a, HCs	0.6%	0.3%	35%*
Commercial Refrigeration	Small Hermetic Stand-Alone Refrigeration Units	2,400,000	247,400	10	0.5	HFC-134a, R-404A, R-407C, HCs	1%	1.5%	40%*
	Condensing Units	600,000	47,440	14*	5*	HFC-134a, R-404A, R-407A, R-407F,R-410A, R-507, HCs	2%	10%	15%
	Centralised Supermarket Refrigeration Systems	109,100,000 (m^2)	10,135,722 (m^2)	18*	0.26 (kg/m^2)	HFC-134a, R-404A, R-407A, HCs, R-717, R-744	2%	18%	8%
Transport Refrigeration	Land Transport Refrigeration	87,210	13,506	7	4	HFC-134a, R-404A	0.2%	15%	20%
	Marine Transport Refrigeration	527	30	25*	1,500*	R-404A, R-407C, R-717	1%	40%	30%
Industrial Refrigeration	Industrial Systems	20,000	764	25*	65	HFC-134a, R-404A, R-407C, R-410A, R-507, HCs, R-717, R-744	1%	8%	15%
Stationary Air-Conditioning	Small Stationary Air Conditioning	4,590,202	615,160	13	1.5	R-407C, R-410A	0.5%	3%	30%
	Medium Stationary Air Conditioning	630,000	52,268	15	15	R-407C, R-410A	1%	6%*	30%
	Large Stationary Air Conditioning (Chillers)	40,000	2,129	18	180	HFC-134a, R-407C, R-410A, R-717	0.5%	3%	20%
	Heat Pumps	20,270	9,632	15	3	HFC-134a, R-404A, R-407C, R-410A	1%	6%*	35%*
Mobile Air-Conditioning	Light Duty Mobile Air Conditioning	27,859,726	1,340,061	15	0.73	HFC-134a	0.5%	10%	30%
	Other Mobile Air Conditioning	499,168	87,502	10	4*	HFC-134a, R-407C	0.5%	10%	30%

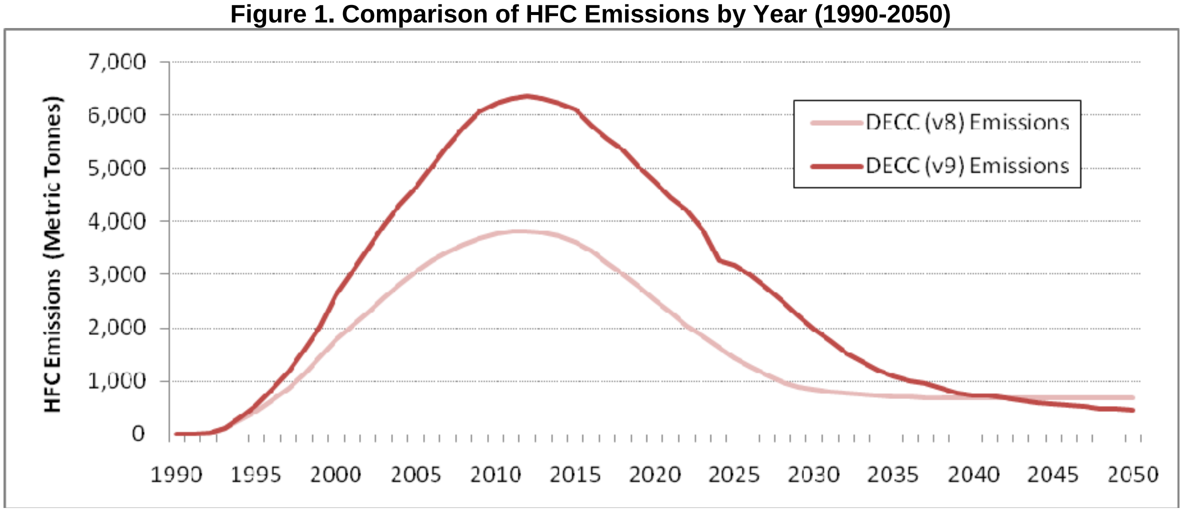
[a] Except where otherwise noted.
* Estimates fall outside of the IPCC (2000) range but are in line with UK- and/or EU-specific estimates provided by industry or in the published literature.

The model structure was also significantly revised to make the model easier to understand, use, and update. Significant changes to the model structure include the reorganization of tabs by end-use, the addition of ODS and alternative refrigerants, the general streamlining of calculations to reduce redundancies, and the addition of output files that are consistent with tables to be consistent with Section 2.F.1 ("Refrigeration and Air-Conditioning Equipment") of the Common Reporting Format (CRF), Calculations were also tailored to account for differences in servicing activities, retrofit activities, and CFC/HCFC phaseout dates.

In the process of finalising the revised model, ICF conducted an analysis to compare estimated refrigerant consumption (as calculated by the model as the amount of refrigerant used to manufacture new equipment produced in the UK plus the amount used to service leaking equipment) with annual refrigerant production data from the British Refrigeration Association (BRA). Following the comparison, assumptions were adjusted as deemed appropriate to further align the model output with the BRA data.

Based on a comparison of the previous version of the DECC model and the revised version of the DECC model, it was found that HFC consumption estimates (i.e., the amount used to manufacture new equipment produced in the UK plus the amount used to service leaking equipment) closely align through the 1990s, but are slightly higher in the revised model from about 2000 to 2025 and lower beyond 2030. The revised model's higher consumption estimates in recent years is consistent with other top-down data (see Section 6), and corrects for the previous model's underestimates that were noted in AEA (2011).[1] The reduced consumption beyond 2025 is the result of the new model's improved projections of the transition away from HFCs. In addition, the estimated HFC emissions generated from the revised version of the model align well with observed emissions data (see Section 6), but are significantly greater than the emissions estimated from the previous version of the model. The discrepancy between the two versions of the models is largely due to the difference in disposal emissions assumptions, which are assumed to be much greater in the revised model, and to the revised definitions/further disaggregation of end-uses—including marine transport, other MACs, and building AC.

Figure 1. Comparison of HFC Emissions by Year (1990-2050)



ICF conducted a Tier 2 quantitative uncertainty analyses for 1995 (base year) and 2010. The results of the analysis indicate a range of approximately 5% below and 6% above the 1995 emission estimate, and approximately +/-5% around the 2010 emission estimate. The most significant sources of uncertainty include the emission factors for centralised supermarket refrigeration systems and marine transport refrigeration—two end-uses with a significant installed base of refrigerant (due to large stock and/or charge size).

As a last step, ICF identified potential areas for future research and modelling improvements. Potential activities to improve the model's estimation of GHG emissions and for policy purposes include:

[1] AEA. (2011). "UK Greenhouse Gas Inventory, 1990 to 2009: Annual Report for Submission under the Framework Convention on Climate Change." April 2011. ISBN 978-0-9565155-4-4. Available at: http://uk-air.defra.gov.uk/reports/cat07/1104280910_ukghgi-90-09_main_chapters_issue2.pdf

Improvements to GHG Estimates

1. Add a retrofit loss rate to account for refrigerant emissions that occur during equipment retrofitting.
2. Further investigate consumption of R-404A vs. HFC-134a in key sectors (i.e., centralised systems, industrial refrigeration).
3. Further investigate UK stock assumptions for condensing units.
4. Conduct additional research on the UK industrial refrigeration sector, particularly for the chemicals industry, to refine stock and charge size assumptions for industrial systems.
5. Refine vehicle growth projections based on national projections.
6. Further investigate operational leak rate assumptions for the UK marine transport refrigeration.
7. Consider further reducing leak rates of equipment stocks beyond 2010 based on the effectiveness of the leak reduction provisions set out under Regulation (EC) No. 842/2006.
8. Adjust model loss rates and/or refrigerant transitions as appropriate to account for any future EC or UK Regulations (e.g., HFC phase-down, further emission reduction initiatives, etc.).
9. Update input assumptions based on IPCC (2006), once guidelines are approved.
10. Refine other input assumptions as new industry data become available.
11. Conduct research on the export of disposed equipment for reuse.
12. Improve the uncertainty analysis by further exploring uncertainty bounds, employing more tailored probability density functions, and refining the uncertainty model calculations for operational emissions.

Improvements for Policy Purposes

13. Develop tailored charge size and leak rate assumptions for ODS and natural refrigerants.
14. Incorporate climate impacts of ODS and natural refrigerants.
15. Improve the modelling of ODS retrofits and phaseout dynamics.
16. Expand the model to include energy efficiency considerations.

Acronyms

AC	Air Conditioning
ASHP	Air source heat pumps
BAU	Business-as-usual
BRA	British Refrigeration Association
CBI	Confidential business information
CFC	Chlorofluorocarbon
CO_2	Carbon dioxide
CRF	Common Reporting Format
DECC	Department of Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
EC	European Commission
EIA	Environmental Investigation Agency
EOL	End-of-life
EPEE	European Partnership for Energy and the Environment
EU	European Union
GDP	Gross domestic product
GSHP	Ground source heat pumps
GT	gigatonne
GWP	Global warming potential
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
IGD	The Institute of Grocery Distribution
kg	kilogram
kW	kilowatt
MAC	Mobile air conditioner
MT	metric tonnes
MTP	Market Transformation Programme
ODS	Ozone depleting substance
IPCC	Intergovernmental Panel on Climate Change
IIR	International Institute of Refrigeration
RTOC	Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee
TEAP	Technology and Economic Assessment Panel
UNFCCC	United Nations Framework Convention on Climate Change
VRF	Variable refrigerant flow

1 Introduction

The objective of this project was to review and update DECC's refrigeration and air conditioning (AC) emissions model so that it can produce more accurate and transparent emission estimates within a functional, flexible modelling framework that can also be used as a policy tool. More specifically, the aim of the research was to:

1. Feed improved and more transparent GHG emissions estimates into the UK national GHG emissions inventory report (as submitted to the UNFCCC) and improve emission projections for non-CO_2 gases;
2. Allow for improved tracking of GHG emission reductions across specific refrigeration/AC sector sub-divisions (or equipment "end-uses") to measure against national GHG reduction goals;
3. Enable testing of policy effectiveness and "what-if" scenarios; and
4. Project a consistent time series from 1990-2050.

As part of this work, ICF addressed suggestions provided by the UNFCCC on DECC's 2010 inventory and performed other model improvements based on the best available data and consideration of other country inventories/best practices. These priority model improvements included: the addition of new end-uses (heat pumps, other transport refrigeration, and other mobile AC); use of bottom-up data across all end-uses; addition of ODS and natural refrigerants; incorporation of likely future market conditions pertaining to the transition away from HFC refrigerants through 2050; and enhanced model functionality and transparency.

This report summarises the approach taken, detailed research findings, and associated model updates that resulted from this effort. A comparison of the revised model output with the previous model output and UK refrigerant production data is also provided. Finally, areas for additional research and model improvements are identified.

2 Approach/Method

To update DECC's refrigeration and AC emissions model from a largely top-down approach (based on total refrigerant sales data) to a bottom-up approach (based on equipment stocks and average charge size from available market data), ICF revised both the model structure and expanded and improved upon the input assumptions for each end-use. Prior to making any updates, the previous model's structure and assumptions were reviewed to identify strengths, weaknesses, uncertainties, and areas for improvement. ICF coordinated with DECC to clarify any questions and then prioritised efforts to most efficiently update the model.

To revise the model structure, calculations were reviewed and updated to reduce redundancies and streamline programming. The organisation of the model was also restructured to make it more user-friendly and easier to follow. Finally, new output files were developed to enable DECC to use the model to inform policy and decision-making. As part of this effort, ICF configured output tables to be consistent with section 2.F.1, "Refrigeration and Air-Conditioning Equipment," of the Common Reporting Format (CRF) to facilitate entry into the UK national GHG emissions inventory report, as submitted to the UNFCCC.

To expand and refine the end-use input assumptions, an extensive literature review was conducted and key industry stakeholders were contacted. As a first step, literature from a broad range of sources was consulted in June/July 2011, including those developed by government and non-government organisations, trade associations, and other institutions. Simultaneously, ICF contacted priority industry stakeholders (selected based on representation across all end-uses) to complement the information found in the literature. Following the development of preliminary assumptions for all end-uses, ICF shared the draft assumptions with a broader range of stakeholders in August/September 2011 to solicit additional industry input. Appendix A provides a listing of the stakeholders contacted as well as a summary of those who provided feedback. Additionally, a list of references used to form the assumptions for each end-use are provided at the end of each subsection in Section 4.

In developing modelling input assumptions by end-use, ICF applied expert judgment to select appropriate values when more than one estimate was provided by literature and/or stakeholders. In general, more weight was given to estimates that are UK-specific and/or more recent. In cases of equal data quality where numerous data points were available, values were selected based on the mid-point of the data range. Where no UK-specific information was available, ICF relied on the 2000 Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance default assumptions to estimate emissions. The 1996 and 2006 IPCC reports were also reviewed and considered, but the latter (most recent) assumptions could not be adopted at this time without additional supporting information, per IPCC guidance. The table below summarises the default assumptions from the IPCC 2000 Good Practice Guidance.

Table 3. IPCC (2000) Default Charge Size, Lifetime, and Leak Rate Assumptions

End-Use	Charge (kg)	Lifetimes (years)	Initial Emission	Lifetime Emission	End-of-Life Emission (recovery efficiency)
Domestic Refrigeration	0.05 ≤ c ≤ 0.5	12 ≤ t ≤ 15	0.2 ≤ e ≤ 1	0.1 ≤ e ≤ 0.5	70% of remainder
Stand-alone Commercial Applications	0.2 ≤ c ≤ 6	8 ≤ t ≤ 12	0.5 ≤ e ≤ 3	1 ≤ e ≤ 10	70 ≤ r ≤ 80% of remainder
Medium & Large Commercial Refrigeration	50 ≤ c ≤ 2000	7 ≤ t ≤ 10	0.5 ≤ e ≤ 3	10 ≤ e ≤ 30	80 ≤ r ≤ 90% of remainder
Transport Refrigeration	3 ≤ c ≤ 8	6 ≤ t ≤ 9	0.2 ≤ e ≤ 1	15 ≤ e ≤ 50	70 ≤ r ≤ 80% of remainder
Industrial Refrigeration including Food Processing and Cold Storage	10 ≤ c ≤ 10K	10 ≤ t ≤ 20	0.5 ≤ e ≤ 3	7 ≤ e ≤ 25	80 ≤ r ≤ 90% of remainder
Chillers	10 ≤ c ≤ 2000	10 ≤ t ≤ 30	0.2 ≤ e ≤ 1	2 ≤ e ≤ 15	80 ≤ r ≤ 95% of remainder
Residential and Commercial A/C, including Heat Pumps	0.5 ≤ c ≤ 100	10 ≤ t ≤ 15	0.2 ≤ e ≤ 1	1 ≤ e ≤ 5	70 ≤ r ≤ 80% of remainder
Mobile Air Conditioners	0.8	12	0.5	10 ≤ e ≤ 20	40% of remainder

In projecting the business-as-usual (BAU) refrigerant transitions to 2050, ICF considered that the UK's commitment to a low-carbon economy[2] will result in HFC use becoming increasingly constrained over time. ICF also considered that numerous factors will impact the rate at which each end-use actually transitions to low-GWP refrigerants—including whether regulations are in place to require the transition (i.e., for MACs); whether sectors are consumer-facing (e.g., supermarkets); and whether safe, economical, and energy-efficient alternatives are available. As a result, in addition to reviewing literature and consulting industry, ICF relied on in-house expertise to develop reasonable assumptions for what the future might look like in an increasingly carbon-constrained economy to develop BAU refrigerant projections through 2050. ICF also considered the impact of Regulation (EC) No. 842/2006 on certain fluorinated greenhouse gases (the F-gas Regulation) by assuming a decrease in the leakage rates of most types of new equipment over time (in response to enhanced recovery rates, as well as technology improvements).

As a final step to further validate the bottom-up assumptions developed for the revised DECC model, total refrigerant consumption (i.e., the amount used to manufacture new equipment produced in the UK plus the amount used to service leaking equipment) calculated by the model was compared with UK production data provided by BRA (2011).[3] Following the comparison, assumptions were adjusted as deemed appropriate to further align the model output with the BRA data. The detailed final results of this comparison are provided in Section 5.

[2] Under the United Nations Framework Convention on Climate Change (UNFCCC), the United Kingdom committed to reduce GHG emissions and report on their progress on an annual basis. In addition, the UK passed the Climate Change Act in 2008, which introduced long-term, legally binding framework to confront climate change. Under this Act, the UK must transition to a low-carbon economy and reduce its GHG emissions by at least 34% of the 1990 baseline by 2020, and by 80% of the 1990 baseline by 2050.

[3] UK Market Statistics 2010: Refrigeration Equipment and Components. Includes refrigerant sales data for 2006, 2007, 2008, 2009, and 2010.

3 Summary of Structural Model Updates

3.1 General Reorganisation and Streamlining

ICF has reorganised the model in order to facilitate continued improvement. The model now contains a General Inputs sheet, which houses the model's master refrigerant list, global warming potentials, and other assumptions and inputs common to all end-uses, sheets for each end-use, and a series of calculation and summary worksheets. Each worksheet is explained in detail below. The model also now uses a consistent colour-coding scheme to facilitate future data entry and model updates. The colour scheme is summarised on the introductory sheet of the model.

3.1.1 General Inputs Sheet

The General Inputs sheet houses the master list of refrigerants used throughout the tool and calculates their global warming potentials (GWPs). The first table in the worksheet, Table A, shows the master refrigerant list and calculates the GWP based on the refrigerant's component chemicals. GWPs for the component chemicals are entered into the second table on the worksheet, Table B. GWPs are entered for the IPCC's second, third, and fourth assessment reports, and space is also provided for users to enter an additional GWP source.

The GWP source used throughout the model is selected from the drop-down menu in cell I11. Note that values from the IPCC Second Assessment Report (SAR) are consistent with the values that must be used in GHG inventories in the first commitment period of the Kyoto Protocol. Users may also enter additional refrigerants at the bottom of the chemical list and, as needed, can enter information on any components of that refrigerant in the empty columns at the right of Table A and GWP information for new components in the empty rows at the bottom of Table B.

The General Inputs sheet also houses general unit conversion factors used throughout the model, as well as assumptions that apply to all retrofits (i.e., replacement of equipment charge with a new refrigerant type).

3.1.2 Summary by End-Use

ICF reorganised the tool so that each end-use is represented on its own Excel worksheet (in the previous system, each gas had its own worksheet). This allows users to easily review all the key assumptions for a given end-use at the same time. Each end-use sheet is split into four parts: (1) data inputs used by calculations; (2) disaggregated annual consumption by specific chemical; (3) retrofit assumptions; and (4) market data specific to each end-use used to build up calculations. All parts are structured similarly for all end-uses, and each of these parts is described in detail below.

Part 1 of the sheet contains the data inputs that are used by the calculations (see Figure 2). These include the end-use name; lifetime; annual refill status; average charge size; and emission rates for manufacture, operations, and disposal. The "Retrofit table start cell:" communicates the presence of retrofits to the model and is not an entry, while "Post-2010 Leak Reductions" controls whether or not reductions in annual leakage are assumed to occur in existing equipment beginning in 2010 as a result of the leak checking/repair provisions specified under Regulation (EC) No. 842/2006 on certain fluorinated greenhouse gases (the F-gas Regulation). Input cells are shaded in yellow for easy identification. Emissions rates are expressed as fractions.

Figure 2: End-use input sheet, Part 1

End-Use Name:	**Domestic Refrigeration**
End-Use Number:	RAC-1
CRF End-Use Category:	Domestic Refrigeration
Lifetime (years):	15
Does this end-use assume refill?	No
Post-2010 Leak Reductions?	No
Retrofit table start cell:	None

Inputs

	1990	1991	1992	1993	1994	199
Average Charge Size (kg)	0.25	0.24	0.23	0.21	0.20	0.1
Manufacturing Loss Rate	0.6%	0.6%	0.6%	0.6%	0.6%	0.6
Operation Loss Rate	1%	1%	1%	1%	1%	1
Disposal Loss Rate	65%	63%	60%	58%	55%	53
Percentage Imported Pre-Charged	90%	90%	90%	90%	90%	90

Part 2 of the sheet contains the table that disaggregates annual consumption to specific refrigerants (see Figure 3). It also includes the total existing stock of refrigerants for the starting year of the model, 1990 (i.e., all equipment in use in the year 1990). The table only shows chemicals actually used in the end-use. Rows for all other chemicals exist, but are hidden. Columns A and B to the left of the table contain flags that enable the model to hide the rows and run calculations only when a chemical is used. This speeds up the model run and makes it easier for users to visualise the refrigerants used in each end-use. This table, shown in the screenshot below, does not consist of inputs. Instead, it contains links to calculations determined by the fourth part of the input sheet. When calculations in the fourth part of the sheet are updated to include consumption for additional chemicals, those rows are automatically unhidden. New chemicals for any end-use should be added into the master chemical list on the General Inputs (a detailed guide to updating the model is provided in Section 2.5, below). The chemicals will appear on the end-use sheet.

Figure 3: End-use input sheet, Part 2 (RAC-3, condensing units, shown)

Chemicals Used in the UK (tonnes)
Calculated based on activity data below

	Retrofit?		Existing Stock	Used in New Equipment				
			1990	1990	1991	1992	1993	1994
Show	0	CFC-12	507.43	36.24	22.58	20.21	15.36	5.83
Show	0	R-502	507.43	36.24	22.58	20.21	15.36	5.83
Show	1	HCFC-22	676.57	48.33	49.05	74.72	112.64	159.23
Show	0	HFC-32	-	-	-	-	-	-
Show	0	HFC-134a	-	-	2.43	6.12	11.82	19.42
Show	1	R-404A	-	-	0.49	1.22	2.36	3.88
Show	2	R-407F	-	-	-	-	-	-
Show	0	R-410A	-	-	-	-	-	-
Show	0	R-507	-	-	-	-	-	-
Show	0	HFO Type 3	-	-	-	-	-	-
Show	0	HCs	-	-	-	-	-	-
Show	0	R-744	-	-	-	-	-	-

Part 3 of each end-use sheet was added to the model to facilitate the calculation of emission adjustments due to retrofitted products (see Figure 4). The section exists on all end-use sheets even though retrofits do not occur in all end-uses. In these cases, Part 3 is empty, but could be used to model retrofits in the future. Part 3 shows which chemicals are involved in retrofits, when the retrofits occur, and what percentage of eligible equipment is retrofitted, with eligibility determined by the lifetime remaining and thresholds entered on the General Inputs sheet. The "Lifetime remaining low threshold" refers to the minimum number of years remaining in equipment's lifetime in order to be eligible for retrofitting; the "Lifetime remaining high threshold" refers to the maximum number of years remaining. In other words, it is assumed that equipment is not retrofitted if it is too new or too old. See the screenshot below, shown for RAC-3, condensing units.

Figure 4: End-use input sheet, Part 3 (RAC-3 shown)

Retrofits

	%	Years
Lifetime remaining low threshold	25%	3
Lifetime remaining high threshold	75%	10

Percent of Existing Equipment Retrofitted

Original	New	1990	1991	1992	1993	1994	1995
CFC-12	HCFC-22	-	-	-	-	-	-
R-502	HCFC-22	-	-	-	-	-	-
HCFC-22	R-422D	-	-	-	-	-	-
R-404A	R-407F	-	-	-	-	-	-

End

Part 4 is uniquely configured for each end use, and contains market data specific to the end use which is used to build up the calculations presented in Part 2 (see Figure 5). The market data calculations follow a similar structure for all end-uses, but because the available data vary between end-uses in terms of refrigerant type, year of initial adoption, and other market characteristics, this flexibility is important. Part 4 first summarises the stock assumptions for each end-use, such as total market size for any available years as well as growth rates used to forecast and back-cast stocks.

Next, those assumptions are input into the Market Data table to estimate the number of new units entering the market for each end-use annually. First, stock for each year is projected across the entire time series based on available stock data and assumed growth rates. The new units are assumed to be the difference between the stock in a given year minus the number of units remaining from the previous year. The number of units remaining from the previous year is the total stock minus the units disposed, which represents all units reaching the end of their lifetime. Representative stock assumptions and market data assumptions are shown in the screenshot below for RAC-5, industrial systems. This format is used across all end-uses.

Figure 5: End-use input sheet, Part 4, stock assumptions and market data (RAC-5 shown)

Stock Assumptions

Year	**Estimate/Assumption**
1990-2009	Back-cast 2010 stock based on historical GDP
2010	**20,000 systems** based on the assumption that there are1,000+ facilities which contain ~17 systems each (Defra 2011; Gluck
2011-2020	2% annual growth rate (Honeywell 2011, STAR Refrigeration 2011, Gluckman 2011; EC 2010; Oko-Recherche 2011)
2021-2030	1% annual growth rate (Honeywell 2011, STAR Refrigeration 2011, Gluckman 2011; EC 2010; Oko-Recherche 2011)
2031-2050	0% annual growth (ICF assumption)

Market Data

	1990	1991	1992	1993	1994	1995	1996	1997	1998
Stock	12,676	12,676	12,688	12,967	13,525	13,944	14,349	14,822	15,356
New Units	507.02	507	520	786	1,065	926	911	981	1,041
Disposed Units	507.02	507.02	507.02	507.02	507.02	507.02	507.02	507.02	507.02
Remaining from previous year		12,169	12,169	12,181	12,460	13,018	13,437	13,842	14,315
GDP Growth Rate	0.8%	0.0%	0.1%	2.2%	4.3%	3.1%	2.9%	3.3%	3.6%
Projected Growth Rate									

However, based on data availability for each end use, additional information is sometimes necessary to estimate stock and sales data. For example, RAC-13, Other Mobile Air-Conditioning, aggregates assumptions for the various vehicle categories included in this end-use, resulting in a much larger market data section in Part 4.

The next component of Part 4 shows the assumptions for what refrigerants are used in new equipment in end-use in each year (see Figure 6). The table shows the assumptions for refrigerant transitions, including market breakdowns for any available years. The table also expands these assumptions, making linear projections between years for which data are available (in white cells). The expanded table showing the proportion of refrigerants in new equipment is multiplied by the new equipment and charge size for each year to generate the table in Part 2.

Figure 6: End-use input sheet, Part 4, refrigerant assumptions (RAC-7 shown)

Proportion of Refrigerants Used in New Equipment

	1990	1991	1992	1993	1994	1995	1996
CFC-11	-	-	-	-	-	-	-
CFC-12	60%	48%	36%	24%	12%	-	-
R-502	-	-	-	-	-	-	-
HCFC-22	40%	50%	60%	70%	80%	90%	75%
HFC-32	-	-	-	-	-	-	-
HFC-134a	-	0%	0%	1%	1%	1%	3%
R-404A	-	0%	0%	1%	1%	1%	2%
R-407A	-	-	-	-	-	-	-
R-407C	-	1%	3%	4%	6%	7%	18%
R-407F	-	-	-	-	-	-	-
R-410A	-	0%	0%	1%	1%	1%	3%
R-417A	-	-	-	-	-	-	-
R-422A	-	-	-	-	-	-	-
R-422D	-	-	-	-	-	-	-
R-507	-	-	-	-	-	-	-
HFO Type 1	-	-	-	-	-	-	-
HFO Type 2	-	-	-	-	-	-	-
HFO Type 3	-	-	-	-	-	-	-
HFO-1234yf	-	-	-	-	-	-	-
HCs	-	-	-	-	-	-	-
R-717	-	-	-	-	-	-	-
R-744	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

As a result of these changes, users can view and edit all of the inputs for a particular end-use on a single page. In later steps (described below), the calculations are performed and then summed by chemical across end-uses. Additional end-uses can be added in a modular fashion by creating a new input sheet based on this pattern.

3.1.3 Blends

The original model listed each chemical formulation separately for each end-use, listing neat compositions and blends. ICF has revised the model such that each end-use sheet only shows the blends and chemicals in the forms that are actually used in the equipment. The component chemicals are disaggregated later in the model flow as necessary to generate inventory outputs by chemical. This allows users to focus only on the products used in an end-use when focusing on that particular end-use.

3.1.4 Future HFOs

HFOs (hydrofluoro-olefins), or unsaturated HFCs, are now beginning to be used as refrigerants in the UK and will be used increasingly in future, as additional HFOs and HFO blends are developed and brought to market. The specific HFOs/HFO blends that will successfully enter the various market segments will depend on safety,[4] efficiency, and cost. Given the current uncertainty regarding the future HFOs/HFO blends that will be used across the various end-uses, three broad HFO "Types" have been entered into the model defined by GWP, based on product information provided by Honeywell (2011).[5] These HFO types are summarised below in Table 4. It should be noted that the GWP assumed for the HFO already in use in light duty MACs (RAC-12)—i.e., HFO-1234yf— is 4.

[4] HFOs have a small level of flammability.
[5] Honeywell. (2011). "Energy Efficiency and Environmental Compliance as Innovation Drivers." Presentation provided to ICF International, July 2011.

Table 4. HFO Categories by GWP and End-Use (For Future Adoption)

HFO Category	Assumed GWP	End-Use
Type 1	5	• Stand alone (RAC-2) • Land transport refrigeration (RAC-10)
Type 2	600	• Small stationary AC (RAC-6) • Medium stationary AC (RAC-7) • Chillers (RAC-8) • Heat pumps (RAC-9)
Type 3	1,000	• Condensing units (RAC-3) • Centralised systems (RAC-4) • Industrial systems (RAC-5) • Marine transport (RAC-11)

These GWP values for HFOs are tentative, and should be updated over time as new HFO products enter the market and more accurate GWP information becomes available.

3.1.5 Addition of ODS and Alternative Refrigerants

Adding ODS and alternative refrigerants to the model will now be relatively straightforward, as formulations can be added to the model by adding them to the master list of available chemicals, or the blend component information to the master refrigerant lists on the General Inputs sheet, as appropriate. Users can add the chemicals to the list in the General Inputs sheet (discussed above) and populate the tables in Part 4 of the relevant end-use sheets. The leak rate and charge size assumptions for ODS and alternative refrigerants will be linked to those for HFCs, as detailed in the Part 1 table; they will not be tailored by refrigerant type. These assumptions, however, will be adjusted to account for changes over time, as is done in the current model structure. More detailed instructions on updating the model are provided in Section 2.5.

3.2 Calculations

In our second major change, ICF has replaced the emissions calculation tables that appeared on each chemical sheet with a single calculation sheet and Visual Basic for Applications (VBA) code that runs the calculations for each end-use/chemical combination and stores the results. The main advantage of this system is that it allows the calculations to be reviewed and edited in a single place. In the previous version, the calculations were repeated on each tab and for each end-use, resulting in 153 sets of calculations (17 gas and blend tabs x 9 end-uses). There are minor calculation differences by end-use for certain end-uses, and these have been programmed into the formulas as appropriate. We have used standard IPCC formulae throughout.

Figure 7: Calculation Inputs

	Current End-Use Name:	**Small Stationary Air Conditioning**						**Run Model**		
	Current End-Use Number:	RAC-6								
	CRF End-Use Category:	Stationary Air-Conditioning								
	Lifetime (years):	13								
	End-Use Assumes Refill?	TRUE								
	Post-2010 Leak Reductions?	FALSE								
	Refrigerants in the UK (tonnes)									
	'RAC-6'!$C$26:$BM$57	Existing Stock	Used in New Equipment							
		1990	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**199**
0	CFC-11	-	-	-	-	-	-	-	-	-
0	CFC-12	473.24	36.40	72.44	58.05	41.46	22.27	-	-	-
0	R-502	-	-	-	-	-	-	-	-	-
0	HCFC-22	315.49	24.27	75.46	96.75	120.93	148.46	179.88	161.85	140.13
0	HFC-32	-	-	-	-	-	-	-	-	-
0	HFC-134a	-	-	0.30	0.64	1.04	1.48	2.00	5.39	9.34
0	R-404A	-	-	0.30	0.64	1.04	1.48	2.00	3.60	5.45
0	R-407A	-	-	-	-	-	-	-	-	-
0	R-407C	-	-	2.11	4.51	7.26	10.39	13.99	37.76	65.39
0	R-407F	-	-	-	-	-	-	-	-	-
0	R-410A	-	-	0.30	0.64	1.04	1.48	2.00	7.19	13.23
0	R-417A	-	-	-	-	-	-	-	-	-
0	R-422A	-	-	-	-	-	-	-	-	-
0	R-422D	-	-	-	-	-	-	-	-	-
0	R-507	-	-	-	-	-	-	-	-	-
0	HFO Type 1	-	-	-	-	-	-	-	-	-
0	HFO Type 2	-	-	-	-	-	-	-	-	-
0	HFO Type 3	-	-	-	-	-	-	-	-	-
0	HFO-1234yf	-	-	-	-	-	-	-	-	-
0	HCs	-	-	-	-	-	-	-	-	-
0	R-717									

The new calculation sheet consists of two parts. The first part, shown in Figure 7, uses the name listed under "Current End Use Name" to pull data from the proper end-use sheet. The data pulled include variables and the consumption data listed in Parts 1 and 2 of the input sheets. A user can look at the calculations for a particular end-use by selecting it from a drop-down box. Otherwise, clicking the "Run Model" button triggers the model to calculate and store the results for each end-use.

The second section is the table in which the calculations are performed (see Figure 8). Only one chemical may be shown at a time. A user can look at the calculations for one chemical, or use the Run Model button to calculate and store the results for each end-use/chemical combination.

Figure 8: Calculation Table

	Output Calculations												
	Current Chem:	HFC-134a		Update Retrofit Calculations for Current Chemical and End-Use									
	Chemical Usage (tonnes)	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
CalcSta	1990 Refrigerant Stock	**0.00**											
1	Refrigerant in All New Equipment	0.00	14.56	29.22	43.97	75.37	106.95	138.73	170.69	202.83	235.15	267.64	386.15
2	Refrigerant in New Equipment (Manufactured in the UK only)	0.00	14.56	29.22	43.97	75.37	106.95	138.73	170.69	202.83	235.15	267.64	386.15
3	Used for Topping Up Units	0.00	2.84	8.39	16.53	30.09	48.81	72.39	100.56	133.01	169.46	209.60	262.76
4	Consumed for Retrofits	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	Total Refrigerant Consumption (All New & In Service Equipment)	0.00	17.47	37.76	60.72	105.83	156.30	211.81	272.10	336.86	405.79	478.59	650.84
6	Total Refrigerant Consumption in the UK (Manufactured in the UK & All In Service Equipment)	0.00	17.47	37.76	60.72	105.83	156.30	211.81	272.10	336.86	405.79	478.59	650.84
7	Size of Bank	0.00	14.56	43.78	87.76	163.12	270.07	408.80	579.49	782.32	1017.48	1285.12	1656.71
8	Refrigerant Remaining in Products Being Disposed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.56
9	Disposal Recycling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.88
10	Virgin Manufacture	0.00	17.47	37.76	60.72	105.83	156.30	211.81	272.10	336.86	405.79	478.59	641.96
11													
12	*Calculation Factors*												
13	Manufacturing Loss Rate	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
14	Operation Loss Rate (or Leak Factor)	0.2	0.195	0.19	0.185	0.18	0.175	0.17	0.165	0.16	0.155	0.15	0.145
15	Disposal Loss Rate	0.5	0.49	0.48	0.47	0.46	0.45	0.44	0.43	0.42	0.41	0.4	0.39
16	Percentage of Units Imported Pre-Charged	0	0	0	0	0	0	0	0	0	0	0	0
17	Current Chemical GWP	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300
18													
19	*Adjustments for Retrofits (tonnes)*												
20	Retrofit Operational Emissions	0	0	0	0	0	0	0	0	0	0	0	0
21	Refrigerant in Retrofitted Products Being Disposed	0	0	0	0	0	0	0	0	0	0	0	0
22	Retrofit Disposal Emissions	0	0	0	0	0	0	0	0	0	0	0	0
23	Retrofit Recycling	0	0	0	0	0	0	0	0	0	0	0	0
24													
25	*Emissions (tonnes)*												
26	Manufacturing Emissions	0.00	0.07	0.15	0.22	0.38	0.53	0.69	0.85	1.01	1.18	1.34	1.93
27	Operational Emissions	0.00	2.84	8.39	16.53	30.09	48.81	72.39	100.56	133.01	169.46	209.60	262.76
28	Disposal Emissions	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.68
29	Total Emissions	0.00	2.91	8.54	16.75	30.47	49.34	73.09	101.41	134.02	170.63	210.94	270.37
30	Potential Emissions	0.00	14.56	43.78	87.76	163.12	270.07	408.80	579.49	782.32	1017.48	1285.12	1656.71
31	Total Emissions, CO_2-equivalent	0.00	3785.91	11098.58	21770.37	39609.94	64146.76	95012.23	131833.02	174231.19	221824.36	274225.84	351476.98

The calculations are broken out into sections and multiple line-items to increase the transparency of the calculation process. The first block of calculations deals entirely with chemical usage and consumption (in tonnes) and shows each form of chemical usage in the UK for every model year. The methodology of these calculations is summarised in Table 5 below.

Table 5: Chemical Usage Calculations

Variable	Formula
1990 Stock	1990 stock (units) × charge size
Refrigerant in All New Equipment	New Units × Charge Size (kg/unit) × 0.001 Tonnes/kg × % applied to each refrigerant
Refrigerant in New Equipment (Manufactured in the UK only)	Refrigerant in All New Equipment × (1 - % imported pre-charged)
Used for topping up (refilling leaks)	**If end use is not refilled**, then use is 0 **If equipment is refilled**, then use equals Operational emissions **If the refrigerant is a CFC or HCFCs and it is after the phaseout year**, then use equals 0
Consumed for retrofits	Amount of original chemical replaced
Total Refrigerant Consumption (All New & In Service Equipment)	Refrigerant in All New Equipment + Used for topping up + Manufacturing emissions + Consumed for retrofits
Total Refrigerant Consumption in the UK (Manufactured in the UK & All In Service Equipment)	Refrigerant in New Equipment (Manufactured in the UK only)+ Used for topping up + Manufacturing emissions + Consumed for retrofits
Size of Bank	**If 1990**, = 1990 Stock - amount in products being disposed + Refrigerant in All New Equipment - Operational emissions + Used for topping up + Consumed for retrofits **If 1991+**, = Size of bank (prev. year) - amount in products being disposed of + Refrigerant in All New Equipment - Leak Emissions + Used for Topping Up + Consumed for Retrofits **If less than zero** (in case of CFCs and HCFCs after phaseout), =0*
Refrigerant Remaining in Products Being Disposed**	**If current year – 1990 is less than lifetime*****, = 1990 Stock/Lifetime + Refrigerant in retrofitted products being disposed **If equipment is refilled**, = Refrigerant in All New Equipment (lifetime ago) + Refrigerant in retrofitted products being disposed **If equipment is not refilled**, = (Refrigerant in All New Equipment (lifetime ago) + Refrigerant in retrofitted products being disposed) × (1 - Operation Loss Rate)^Lifetime **If CFC/HCFC and after phaseout year**, = (Used in New Equipment in the UK (years ago since phaseout) + Refrigerant in retrofitted products being disposed) × (1 - Operation Loss Rate)^(Years since phaseout)
Disposal Recycling	Refrigerant remaining in products being disposed - Disposal emissions
Virgin Manufacture	Total refrigerant consumption, products manufactured in the UK - Disposal recycling

*Given the difficulties of reconciling the change in treatment of leaks after ODS servicing phaseout dates with concurrent retrofits and the constraints of this model, banks are forced to not go below zero in the case of CFCs and HCFCs. The servicing phaseout date for CFCs is set to 2000, while that for HCFCs is set to 2015.
** Disposal amounts are calculated in a separate sheet, “OpEmissions Table.” These amounts are adjusted for CFC and HCFC servicing phaseouts for original and retrofitted equipment.
*** For example, if 1995-1990 is 5 and lifetime is 14, then equipment being disposed is part of the original 1990 stock.

The next section of the calculation table is Calculation factors. These cells do not house any calculations, but rather pull the applicable emission factors, import percentages, and GWP value. The factors are used to calculate other variables. Prior to the final emission calculations, ICF has also included a section in the calculations for adjustments due to retrofits. These values pull from the Retrofit Calculations sheet, which is explained in more detail below in Section 3.2.3. Simply, these rows allow the model to add or subtract stocks and resulting operational and disposal emissions from chemicals used to retrofit equipment or that are replaced through retrofits, respectively.

The final section of the calculation table is emissions (in tonnes). The emissions are broken down into manufacturing emissions, operational emissions and disposal emissions, as well as total emissions (regular and GWP-weighted) and potential emissions. Loss rate for manufacture, operation, and disposal are provided as a percentage of the original equipment charge. The methodology of these calculations is summarised in Table 6 below.

Table 6: Emissions Calculations

Variable	Formula
Manufacturing Emissions	Refrigerant in equipment manufactured in the UK × Manufacturing Loss Rate
Operational Emissions*	**If equipment is refilled**, = Sum for each year of equipment in operation the Refrigerant used in new equipment × Operational Loss Factor + Retrofit Operational Emissions **If equipment is not refilled**, = Sum for each year of equipment in operation the Refrigerant in new equipment × Operational Loss Factor × (1 – Operational Loss Factor)^Lifetime + Retrofit Operational Emissions
Disposal Emissions	Refrigerant in products being disposed × Disposal Loss Rate
Total Emissions	Manufacturing emissions + Operational emissions + Disposal emissions
Potential Emissions	Size of bank
Total Emissions, CO_2-equivalent	Total emissions × Current chemical Global Warming Potential (GWP)

*Operational emissions are calculated in a separate sheet, "OpEmissions Table." The calculation methodology is explained in Section 2.2.1 below. Operational emissions are also adjusted for CFC and HCFC servicing phaseouts.

3.2.1 Operational Emissions

Operational emissions, referred to as lifetime emissions in the previous model, are calculated in the "OpEmissions table" sheet. Operational emissions include emissions during the use of a product, including those that occur during servicing and from normal or catastrophic leakage. In the model, two formulas are used to calculate operational emissions depending on whether or not HFCs in the equipment are serviced (refilled) annually.

Operational emissions are calculated by multiplying the amount of refrigerant in active products by the operational loss rate, or the percentage of refrigerant in the product that leaks out during the year. The amount of refrigerant in active products depends on whether the products in each end-use are assumed to be refilled annually or not. If the products are assumed to be refilled or "topped-off" annually, then the operational loss factor is applied to the amount of refrigerant in new products; that is, for each year from *Current Year to Current Year – n,* where *n* is the product lifetime. For example, if the product lifetime is five years, then the 2010 leak emissions will equal the Leak Factor multiplied by the sum of refrigerant in new products for 2010, 2009, 2008, 2007, and 2006. The amount of chemical in each product is thus assumed to be constant year after year, implying that the amount of gas that leaks out each year is replaced.

However, if the products in each end-use are not assumed to be refilled, then the amount of refrigerant in products will decrease for every year of the product's lifetime. In other words, the amount of chemicals in each piece of equipment does not stay constant year after year, but rather decreases due to annual leaks. This assumption requires a different method to calculate total leak emissions for any year, accounting for the ever-decreasing amount of chemicals remaining in the equipment. This amount decreases exponentially, as the total leak emissions for a given year need to apply the leak factor to the amount of refrigerant remaining after manufacture *and* after leaks to all active products. For example, the 2010 leak emissions for a product with a lifetime of five years would be equal to the sum of leaks from the following five product vintages:

Leaks from 2010 products = OLR × (2010 Refrigerant in New Equipment in the UK)
Leaks from 2009 products = OLR × *('09 Refrigerant in New Equipment in the UK) × (1 – OLR)*
Leaks from 2008 products = OLR × *('08 Refrigerant in New Equipment in the UK) × $(1 - OLR)^2$*
Leaks from 2007 products = OLR × *('07 Refrigerant in New Equipment in the UK) × $(1 - OLR)^3$*
Leaks from 2006 products = OLR × *('06 Refrigerant in New Equipment in the UK) × $(1 - OLR)^4$*

Where,
OLR = operational loss rate

Italicized components of equations represent quantity of chemicals left in products after leaks from the previous year(s).

The distinction between these methods was contained within the calculations in the original DECC model. ICF has revised the model so that the assumption about end-use product refills is stated up-front for each end-use (see Figure 2). The model can then apply the correct operational emissions methodology based on this declared assumption. The model currently assumes that all but two end-uses—domestic refrigeration (RAC-1) and small hermetic refrigeration units (RAC-2)—are refilled annually. This method allows assumptions about end-uses to be transparent, as well as readily changed if necessary.

Users should note that, although operational loss rates can vary by refrigerant type, the operational emissions calculations are currently intended to reflect only HFC leak rates (i.e., not leak rates for ODS or natural refrigerants). The leak rates vary by year of manufacture, but stay constant over a product's lifetime. The model is able to reduce leak rates for existing equipment—for example, if leakage is believed to decline over time in response to improved leak checking/repair practices. ICF considered using this feature to reduce operational leaks from existing equipment starting in 2010, in response to Regulation (EC) No. 842/2006 that targets leak checking and repair;[6] however, the resulting 2010 model estimates for refrigerant consumption with this assumption were significantly below the top-down BRA refrigerant production data in that year, whereas the model output *without* the assumption aligned very closely. Therefore, the 2010 leak rate adjustment for existing equipment is not used in the current model. To change this assumption for any end-use, users can select "Yes" in the "Post-2010 Leak Reductions?" entry in Part 1 of each end-use sheet.

3.2.2 Disposal Emissions

The model assumes that in any given year for an end-use with a life time of *n,* all units manufactured *n* years ago are disposed. This is easily calculated for all equipment manufactured from 1990 onward. For equipment manufactured before 1990, given an initial 1990 stock of *S* units and a lifetime of *n* years, the model assumes disposal of *S/n* units each year until the pre-1990 units are disposed. The amount of charge left in each equipment at disposal is assumed to equal the original charge for units that are refilled, and equals the original charge minus the sum of operational losses for units that are not refilled. Disposal emissions in each year are calculated by multiplying the disposal loss rate by the amount left in equipment at disposal. The disposal loss rate is expressed as a percentage of the total original charge size. The model assumes the balance of the equipment charge is recycled. This amount is then subtracted from refrigerant consumption in the UK to determine "virgin manufacture," or the amount of new (virgin) chemicals used for manufacture in the UK. This variable reflects the reality that refrigerants may be reused once products containing them are disposed; however, it is not used in any output summaries or comparisons.

3.2.3 Adjustments for CFC and HCFC Phaseout

CFCs (CFC-11, CFC-12) and HCFCs (HCFC-22, R-502) are assumed to be phased out for servicing in 2000 and 2015, respectively. The primary implication of this assumption is that products still active in those years will cease to be refilled. This shift from products being serviced to not serviced has a small impact on the amount of refrigerant in products at disposal and product operational emissions. ICF has created calculations that adjust for operational emissions and disposal emissions due to the CFC/HCFC phaseout on the OpEmissions sheet. ICF was also able to incorporate adjustments for retrofits into these calculations for the amount of chemical disposed in response to the CFC and HCFC phaseouts.

Specifically, to adjust operational emissions from retrofits in response to the CFC/HCFC phaseouts, ICF calculated an adjustment on the Retrofit Calculations sheet. This correction is necessary because the retrofits calculations assume that chemical consumption, operational emissions, and disposal are equal for the original and retrofit chemicals. Those equal amounts are then either subtracted from or added to the original product, respectively. However, this is not true in the case of CFCs/HCFCs, because they are assumed to be retrofitted with HFCs, which will remain in the products beyond the CFC/HCFC phaseout year. Therefore, more HFC chemical will be consumed to fill and service the product over its lifetime than would have been if the product still contained CFCs or HCFCs.

[6] The impacts of Regulation (EC) No. 842/2006 is taken into account in the model in other ways, namely by reducing leak rates from most types of new equipment vintages over time in response to increased recovery, as well as improved technologies.

Thus, for each CFC/HCFC retrofit, ICF has calculated a correction amount that is added to the Operational Emissions row of the Calculations sheet. This adjustment is calculated as follows:

1. Calculate "Retrofit Stock," the amount of retrofit chemicals in end-use products in each year
2. Calculate an Implied Operational Emission Factor (IEF); IEF = Retrofit Operational Emissions / Retrofit Stock
3. Calculate operational emissions adjustment using the implied operational emission factor. Operational emissions adjustment = Retrofit Operational Emissions – Retrofit Stock × IEF × (1 – IEF)^(years since phaseout)

ICF needed to calculate an implied emission factor because the retrofits in a given year apply to products manufactured across multiple years, and therefore with different operational emission rates. This methodology came as close as possible within the framework of this model to calculating operational emissions for products with CFC or HCFC retrofits. The resulting error from this methodology is the difference between the implied emission factor and the operational leak rates for each manufacturing year. On average, the implied emission factor is 2% higher than the average operational emission rates over the retrofitted lifetimes for the retrofitted CFCs and HCFCs (see Table 7)—HFC emissions are *not* affected. Table 7 shows the percent differences between the calculated implied emission factor and the average operational emission factor for the relevant manufacture years for each end-use affected by this issue. There is no difference between these factors for end-uses 4, 5, 7, or 8.

Table 7: Percent Difference between Calculated Implied Emission Factor and Average Operational Emission Factor for Retrofitted Product Manufacture Years

End-Use Affected	Chemical(s) Affected	Percent Difference
RAC-3, Condensing units	CFC-12, HCFC-22	7%
RAC-4, Centralised Supermarket Refrigeration Systems	CFC-12, HCFC-22	0%
RAC-5, Industrial Systems	CFC-12, HCFC-22	0%
RAC-7, Medium Stationary Air Conditioning	CFC-12, HCFC-22	0%
RAC-8, Large Stationary Air Conditioning (Chillers)	HCFC-22	0%
RAC-11, Marine Transport Refrigeration	CFC-12, HCFC-22	1%
RAC-12, Light-Duty Mobile Air Conditioning	CFC-12	3%
Average		**2%**

Any error that may be introduced by this methodology will be minor and not passed on to the data prepared for the CRF, as HFCs are not affected. Moreover, the slightly higher emission rate (of 2% on average) may ultimately compensate for the fact that the model does not currently assume any refrigerant losses during the retrofit process. Future changes to the programming of the model can be made to correct for this modelling deficiency and better account for the market dynamics associated with ODS retrofits and phaseouts; however, such changes are likely to require additional use of VBA, which could potentially reduce calculation transparency

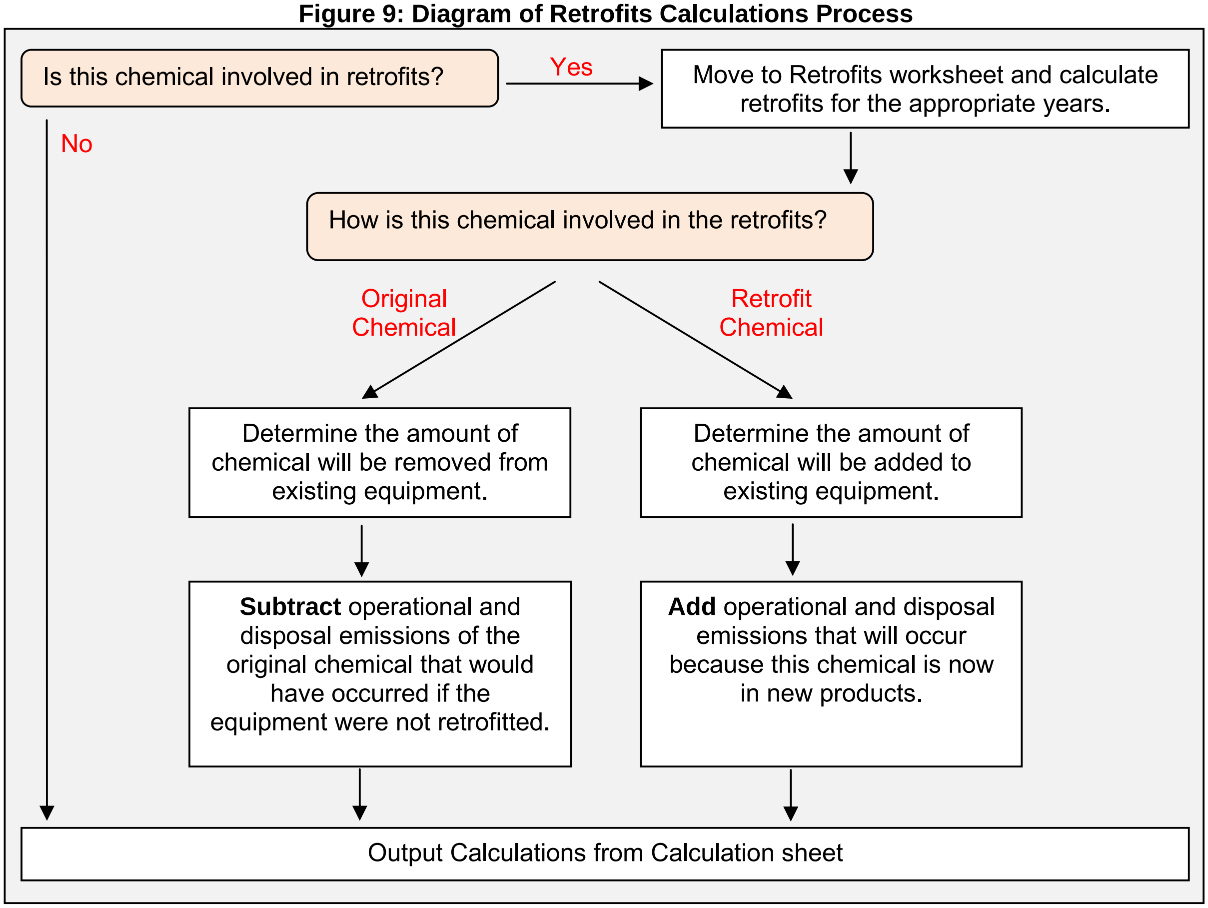
3.2.4 Retrofit Calculations

The model updates enable for the accounting of equipment retrofits, whereby outmoded refrigerants are removed from equipment still in use before their retirement date and replaced with an alternative refrigerant. Currently, retrofits away from ODS and/or HFCs are assumed on all end-uses except domestic refrigeration (RAC-1), small hermetic stand-alone refrigeration units (RAC-2), heat pumps (RAC-9), land transport refrigeration (RAC-10), and other mobile air-conditioning (RAC-13). Retrofit assumptions are entered on each end-use sheet in Part 3, as discussed above in Section 3.2.3. Retrofit assumptions represent the percent of remaining refrigerant in 'eligible' equipment that is replaced by a retrofit refrigerant, which is explained in more detail below.

Adjustments for these retrofits are made on a separate sheet, the Retrofit Calculator sheet, and incorporated into the final calculations for each end-use and chemical. As the model rotates through each end-use and chemical, adjustments will be made if that chemical is involved in retrofits. Calculations are made for all chemicals involved in retrofits, whether they are the original chemical that is replaced, or the retrofit chemical that replaces the original.

When a chemical is involved in a retrofit, the retrofits calculations are triggered such that the amount of original chemical in equipment and the percentage of units in service that are retrofitted are pulled from Parts 2 and 3 of the end-use sheet, respectively. The model then determines the amount of original chemical that is replaced through retrofits for each product manufacture year and retrofit year. For equipment within 'eligible' retrofit lifetimes/years (as calculated in Part 3 of each end-use sheet based on the assumption that, for example, units with between 25% and 75% of their useful lifetime are eligible to be retrofitted; these thresholds can be edited on the General Inputs sheet), the model multiplies the percentage of units retrofitted by the amount of refrigerant remaining in equipment. For the first retrofit year, the percentage applies to the amount of original chemical in equipment. For subsequent retrofit years, the amount of refrigerant retrofitted in earlier years is subtracted from the original chemical total before the percentage is applied. Figure 9 provides a diagram of the retrofit calculations process.

Figure 9: Diagram of Retrofits Calculations Process



In these calculations, it is assumed that there are no losses associated with the retrofitting process itself. The retrofit calculation adjustments are made only to reflect that one chemical has replaced another in a portion of existing equipment

From this, the model calculates three data points, which are calculated depending on whether the current chemical is the original chemical or the retrofit chemical. The first data point is consumption of the current chemical for retrofits. For the retrofit chemical, this equals the total amount of original chemical replaced, and is added to the "Consumed for retrofits" row on the Calculations sheet. For the original chemical, this amount is assumed to be recycled and feeds into the "Retrofit recycling" row of the Calculations sheet. Next, the retrofit calculator calculates operational emissions from retrofitted equipment by multiplying the end-use operational loss factor by the amount of chemical retrofitted. These values are set to be positive for the retrofit chemical and negative for the original chemical, and then added to total operational emissions in the final calculations sheet. This allows the operational emissions from the original chemical to be subtracted out after the chemical is retrofitted. Further adjustments are made to the retrofit operational emissions for CFCs and HCFCs after their phaseout dates (2000 and 2015, respectively), as explained in detail in Section 3.2.3.

Similarly, the retrofit calculator calculates necessary adjustments for disposal of chemicals in retrofitted equipment. The model determines the amount of retrofitted equipment reaching the end of its lifetime, and adds it to the “Refrigerant remaining in products being disposed” row on the Calculations sheet. The value is positive for the retrofit chemical and negative for the original chemical so that it is ultimately subtracted from disposal emissions. Currently, the model is not configured to account for products that are not serviced or refilled to determine retrofit emission adjustments. However, the two end-uses without servicing—domestic refrigeration and small hermetic stand-alone refrigeration units—are not assumed to be retrofitted so the outputs are not affected at this time.

3.3 Enhanced Transparency

The above edits increase the model transparency because it is easier to view all of the inputs for a particular end-use. By replacing hard-coded variables (e.g., lifetime) with dedicated input cells and standardising calculation formulas, users can easily review and update calculations. These changes also facilitate the addition of new end-uses and chemicals as needed. The revised model provides explanations of the key formulas used on the Calculations sheet (below the calculations table). All of the assumptions and data sources used to develop the end use assumptions are noted below in the end-use documentation. In addition, the model now includes a tracking sheet that clearly documents each update made, including entry fields for the user making the change, date, reason for change, and any documentation related to the change. A dialogue box prompting users to input this data appears every time the file is saved. Including this feature ensures that all changes to assumptions (or model code) are properly documented and transparent for future reference. Additionally, it will allow DECC to save multiple versions of the files for use in policy evaluation scenarios; each option is contained separately, and has individual documentation, allowing for easier side-by-side evaluation.

3.4 Generation of Outputs

When the model runs as described above, it copies selected data points for output. The available options are shown in Figure 8 above, and can be expanded or streamlined as needed. The particular outputs the model saves are also flexible, and can be used to meet a variety of analytical and reporting needs, as described below.

3.4.1 Policy-Informing Outputs

The changes described above will allow DECC flexibility in choosing outputs from the model that can inform policy and decision-making. For example, as Defra is responsible for policy areas associated with fluorinated gases and works with other departments to ensure reductions in GHG emissions, this model will serve as a useful tool to help assess the potential impact of GHG reduction policies associated with the refrigeration/AC sector and track progress over time.

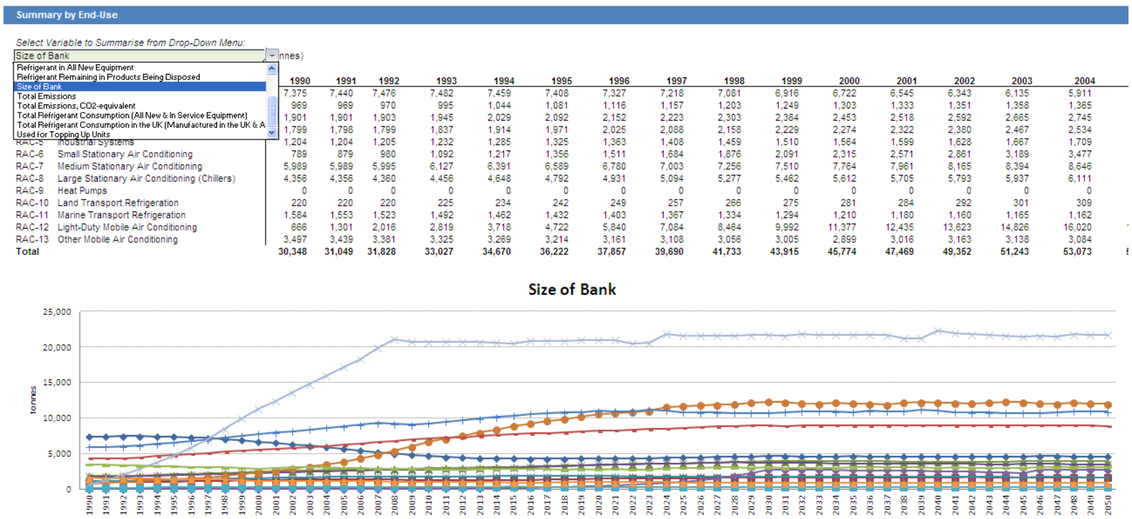
For each end-use, chemical, and year, the model can generate outputs for any of the rows in the Calculations table. It is currently configured to generate outputs for the following variables. Variables marked with an asterisk (*) are required for the national Inventory:

- Refrigerant in All New Equipment
- Refrigerant in New Equipment (Manufactured in the UK only)*
- Total Refrigerant Consumption (Manufactured in the UK & All In Service Equipment)
- Used for Topping Up Units
- Disposal Recycling
- Size of Bank*
- Refrigerant Remaining in Products Being Disposed*
- Manufacturing Emissions*
- Operational Emissions*
- Disposal Emissions*
- Total Emissions
- Total GWP-Weighted Emissions

These outputs can be used to enhance DECC's understanding of the market and inform policy decisions, including enabling testing of policy effectiveness and "what-if" scenarios. In addition, these outputs fit readily into the UNFCCC's CRF reporter, as described in Section 3.4.2. With the proposed tool design, DECC can choose to generate additional outputs from the tool in addition to those required for national inventory reporting.

Summaries for each of the above variables can be found on the Summary sheet. Each variable is summarised by end-use and by chemical. Users can select the variable of interest from the drop-down menu to view a summary table and figure for that variable by end-use or chemical (see screenshot in Figure 10). These charts provide a visual sense of the activity in the refrigeration market over time.

Figure 10: Summary Sheet, select variable from drop-down menu



		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
		7,375	7,440	7,476	7,482	7,459	7,408	7,327	7,218	7,081	6,916	6,722	6,545	6,343	6,135	5,911
		969	969	970	995	1,044	1,081	1,116	1,157	1,203	1,249	1,303	1,333	1,351	1,358	1,365
		1,901	1,901	1,903	1,945	2,029	2,092	2,152	2,223	2,303	2,384	2,453	2,518	2,592	2,665	2,745
		1,799	1,798	1,799	1,837	1,914	1,971	2,025	2,088	2,158	2,229	2,274	2,322	2,380	2,467	2,534
RAC-5	Industrial Systems	1,204	1,204	1,205	1,232	1,285	1,325	1,363	1,408	1,459	1,510	1,564	1,599	1,628	1,667	1,709
RAC-6	Small Stationary Air Conditioning	789	879	980	1,092	1,217	1,356	1,511	1,684	1,876	2,091	2,315	2,571	2,861	3,189	3,477
RAC-7	Medium Stationary Air Conditioning	5,989	5,989	5,995	6,127	6,391	6,589	6,780	7,003	7,256	7,510	7,764	7,961	8,165	8,394	8,646
RAC-8	Large Stationary Air Conditioning (Chillers)	4,356	4,356	4,360	4,456	4,648	4,792	4,931	5,094	5,277	5,462	5,612	5,705	5,793	5,937	6,111
RAC-9	Heat Pumps	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RAC-10	Land Transport Refrigeration	220	220	220	225	234	242	249	257	266	275	281	284	292	301	309
RAC-11	Marine Transport Refrigeration	1,584	1,553	1,523	1,492	1,462	1,432	1,403	1,367	1,334	1,294	1,210	1,180	1,160	1,165	1,162
RAC-12	Light-Duty Mobile Air Conditioning	666	1,301	2,016	2,819	3,718	4,722	5,840	7,084	8,464	9,992	11,377	12,435	13,623	14,826	16,020
RAC-13	Other Mobile Air Conditioning	3,497	3,439	3,381	3,325	3,269	3,214	3,161	3,108	3,056	3,005	2,899	3,016	3,163	3,138	3,084
Total		**30,348**	**31,049**	**31,828**	**33,027**	**34,670**	**36,222**	**37,857**	**39,690**	**41,733**	**43,915**	**45,774**	**47,469**	**49,352**	**51,243**	**53,073**

By altering the inputs to reflect an alternative technological or policy scenario, re-running the model, and comparing to the previous run, DECC will be able to calculate differences among scenarios. In this way, the GHG Refrigeration and Air Conditioning model can serve as a policy tool as well as provide accurate emission estimates for the national inventory.

3.4.2 CRF Reporter Outputs

In addition to using outputs of the model as a policy tool, the model is configured to generate output tables to facilitate entry into the UK national GHG emissions inventory report, as submitted to the UNFCCC through the Common Reporting Format (CRF). The model outputs correspond to CRF section 2.F.1, "Refrigeration and Air-Conditioning Equipment." The sub-components of this section are outlined in Text Box 1, right. This list represents the chemicals required for reporting under each end-use. In the future, changes may be made to the CRF output requirements, which can easily be accommodated in the current model structure, since output can be tailored accordingly. See Section 3.5 for step-by-step instructions on how to update the model outputs and CRF output structure.

Text Box 1. Refrigeration and Air-Conditioning Equipment CRF Table Outline

2.F.1 Refrigeration and Air-Conditioning Equipment
- HFCs
- PFCs
- SF6

2.11A.F.1.1 Domestic Refrigeration
- HFC-134a

2.11A.F.1.2 Commercial Refrigeration
- HFC-125
- HFC-134a
- HFC-143a
- HFC-32
- HFC-152a
- HFC-236fa

2.11A.F.1.3 Transport Refrigeration
- HFC-125
- HFC-143a
- HFC-134a

2.11A.F.1.4 Industrial Refrigeration
- HFC-32
- HFC-125
- HFC-134a
- HFC-143a

2.11A.F.1.5 Stationary Air-Conditioning
- HFC-134a
- HFC-32
- HFC-125

2.11A.F.1.6 Mobile Air Conditioning
- HFC-134a
- HFC-32
- HFC-125

ICF's revisions to the model allow the model to generate CRF tables to populate this section. For the sector as a whole, the CRF Reporter requires three input variables. For each of the end-uses and gases, the CRF reporter requires nine input variables. These input variables correspond to the proposed output variables of the model, as summarised in Table 8. Table 9 provides the corresponding model end-uses as compared with the end-uses defined in the CRF.

As seen in the tables, the proposed model calculations correspond well to the required CRF Reporter inputs. The model can therefore be configured to generate output tables of all necessary values to complete the pertinent CRF Reporter section covering refrigeration and air-conditioning equipment. It should be noted that ICF is proposing to modify the end-use categories in the current model, but the proposed end-use categories also align well with the CRF end-uses.

Table 8. Required CRF Inputs and Corresponding Model Outputs

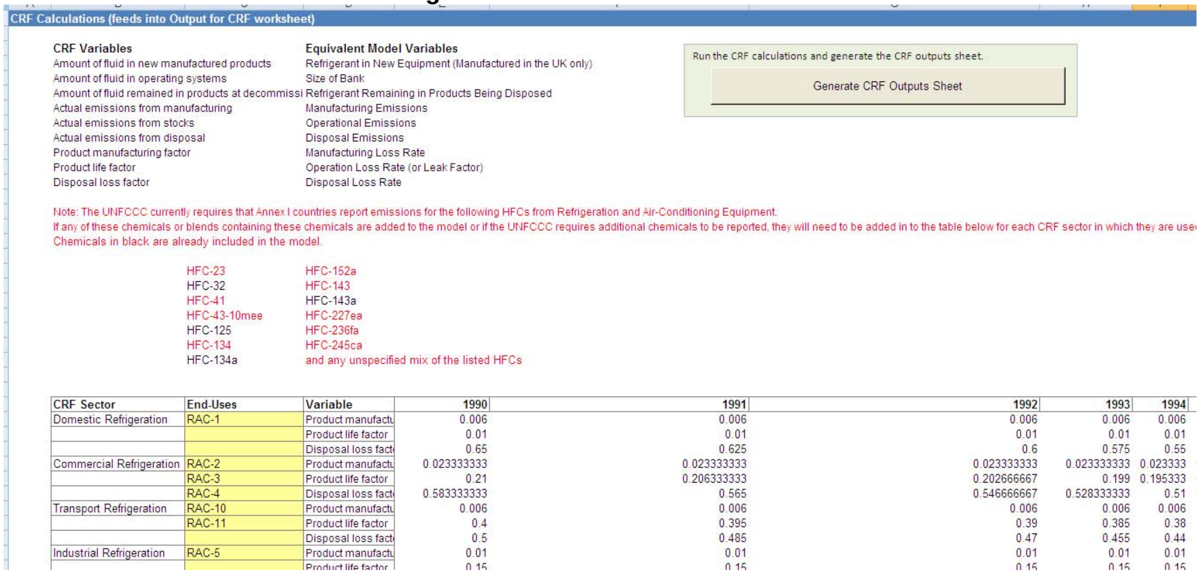
CRF Input Field	Corresponding Model Output
Potential emissions – HFCs (Gg CO_2e)	Potential emissions (summed across all HFCs)
Potential emissions – PFCs (Gg CO_2e)	N/A
Potential emissions – SF_6 (Gg CO_2e)	N/A
Amount of fluid in new manufactured products (t)	Refrigerant in equipment manufactured in the UK
Amount of fluid in operating systems (t)	Size of bank
Amount of fluid remained in products at decommissioning (t)	Refrigerant remaining in products being disposed
Actual emissions from manufacturing (t)	Manufacturing emissions
Actual emissions from stocks (t)	Operational emissions
Actual emissions from disposal (t)	Disposal emissions
Product manufacturing factor (%)	Manufacturing loss rate
Product life factor (%)	Operational loss rate
Disposal loss factor (%)	Disposal loss rate

Table 9. CRF Reporter End-Uses and Corresponding Model End-Uses

CRF Category	Model Corresponding End-Use(s)
Domestic Refrigeration	RAC-1 – Domestic Refrigeration
Commercial Refrigeration	RAC-2 – Small Hermetic Stand-Alone Refrigeration Units
	RAC-3 – Condensing Units
	RAC-4 – Centralised Supermarket Refrigeration Systems
Transport Refrigeration	RAC-10 – Land Transport Refrigeration
	RAC-11 – Marine Transport Refrigeration
Industrial Refrigeration	RAC-5 – Industrial Systems
Stationary Air-Conditioning	RAC-6 – Small Stationary Air Conditioning
	RAC-7 – Medium Stationary Air Conditioning
	RAC-8 – Large Stationary Air Conditioning (Chillers)
	RAC-9 – Heat Pumps
Mobile Air-Conditioning	RAC-12 – Light Duty Mobile Air Conditioning
	RAC-13 – Other Mobile Air Conditioning

On the CRF calculations sheet, the model calculates each of the necessary line items for the CRF reporter, summing by CRF category and disaggregating refrigerant blends as necessary. Click the button on the top of the CRF Calculations sheet (see Figure 11) to generate an all-values output sheet (see Figure 12) for input into the CRF Reporter. The framework for the CRF outputs is currently based on the existing chemicals in the model that are required to be reported to the UNFCCC. If an additional refrigerant is added that requires reporting to the UNFCCC, the CRF outputs framework will need to be adjusted accordingly. See Section 3.5 for step-by-step instructions on how to add refrigerants to the CRF output framework.

Figure 11: CRF Calculations sheet



CRF Calculations (feeds into Output for CRF worksheet)

CRF Variables	Equivalent Model Variables
Amount of fluid in new manufactured products	Refrigerant in New Equipment (Manufactured in the UK only)
Amount of fluid in operating systems	Size of Bank
Amount of fluid remained in products at decommissi	Refrigerant Remaining in Products Being Disposed
Actual emissions from manufacturing	Manufacturing Emissions
Actual emissions from stocks	Operational Emissions
Actual emissions from disposal	Disposal Emissions
Product manufacturing factor	Manufacturing Loss Rate
Product life factor	Operation Loss Rate (or Leak Factor)
Disposal loss factor	Disposal Loss Rate

Run the CRF calculations and generate the CRF outputs sheet.

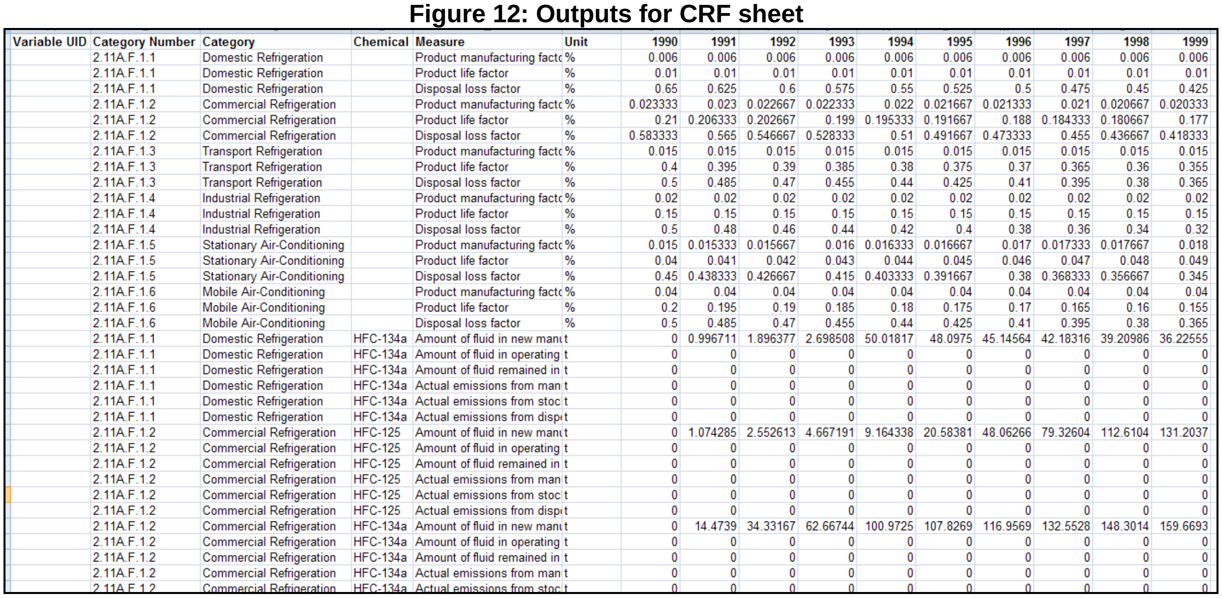
Generate CRF Outputs Sheet

Note: The UNFCCC currently requires that Annex I countries report emissions for the following HFCs from Refrigeration and Air-Conditioning Equipment.
If any of these chemicals or blends containing these chemicals are added to the model or if the UNFCCC requires additional chemicals to be reported, they will need to be added in to the table below for each CRF sector in which they are use
Chemicals in black are already included in the model.

HFC-23	HFC-152a
HFC-32	HFC-143
HFC-41	HFC-143a
HFC-43-10mee	HFC-227ea
HFC-125	HFC-236fa
HFC-134	HFC-245ca
HFC-134a	and any unspecified mix of the listed HFCs

CRF Sector	End-Uses	Variable	1990	1991	1992	1993	1994
Domestic Refrigeration	RAC-1	Product manufactu	0.006	0.006	0.006	0.006	0.006
		Product life factor	0.01	0.01	0.01	0.01	0.01
		Disposal loss fact	0.65	0.625	0.6	0.575	0.55
Commercial Refrigeration	RAC-2	Product manufactu	0.023333333	0.023333333	0.023333333	0.023333333	0.023333
	RAC-3	Product life factor	0.21	0.206333333	0.202666667	0.199	0.195333
	RAC-4	Disposal loss fact	0.583333333	0.565	0.546666667	0.528333333	0.51
Transport Refrigeration	RAC-10	Product manufactu	0.006	0.006	0.006	0.006	0.006
	RAC-11	Product life factor	0.4	0.395	0.39	0.385	0.38
		Disposal loss fact	0.5	0.485	0.47	0.455	0.44
Industrial Refrigeration	RAC-5	Product manufactu	0.01	0.01	0.01	0.01	0.01
		Product life factor	0.15	0.15	0.15	0.15	0.15

Figure 12: Outputs for CRF sheet



Variable UID	Category Number	Category	Chemical	Measure	Unit	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
	2.11A.F.1.1	Domestic Refrigeration		Product manufacturing factc	%	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
	2.11A.F.1.1	Domestic Refrigeration		Product life factor	%	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	2.11A.F.1.1	Domestic Refrigeration		Disposal loss factor	%	0.65	0.625	0.6	0.575	0.55	0.525	0.5	0.475	0.45	0.425
	2.11A.F.1.2	Commercial Refrigeration		Product manufacturing factc	%	0.023333	0.023	0.022667	0.022333	0.022	0.021667	0.021333	0.021	0.020667	0.020333
	2.11A.F.1.2	Commercial Refrigeration		Product life factor	%	0.21	0.206333	0.202667	0.199	0.195333	0.191667	0.188	0.184333	0.180667	0.177
	2.11A.F.1.2	Commercial Refrigeration		Disposal loss factor	%	0.583333	0.565	0.546667	0.528333	0.51	0.491667	0.473333	0.455	0.436667	0.418333
	2.11A.F.1.3	Transport Refrigeration		Product manufacturing factc	%	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
	2.11A.F.1.3	Transport Refrigeration		Product life factor	%	0.4	0.395	0.39	0.385	0.38	0.375	0.37	0.365	0.36	0.355
	2.11A.F.1.3	Transport Refrigeration		Disposal loss factor	%	0.5	0.485	0.47	0.455	0.44	0.425	0.41	0.395	0.38	0.365
	2.11A.F.1.4	Industrial Refrigeration		Product manufacturing factc	%	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	2.11A.F.1.4	Industrial Refrigeration		Product life factor	%	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	2.11A.F.1.4	Industrial Refrigeration		Disposal loss factor	%	0.5	0.48	0.46	0.44	0.42	0.4	0.38	0.36	0.34	0.32
	2.11A.F.1.5	Stationary Air-Conditioning		Product manufacturing factc	%	0.015	0.015333	0.015667	0.016	0.016333	0.016667	0.017	0.017333	0.017667	0.018
	2.11A.F.1.5	Stationary Air-Conditioning		Product life factor	%	0.04	0.041	0.042	0.043	0.044	0.045	0.046	0.047	0.048	0.049
	2.11A.F.1.5	Stationary Air-Conditioning		Disposal loss factor	%	0.45	0.438333	0.426667	0.415	0.403333	0.391667	0.38	0.368333	0.356667	0.345
	2.11A.F.1.6	Mobile Air-Conditioning		Product manufacturing factc	%	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
	2.11A.F.1.6	Mobile Air-Conditioning		Product life factor	%	0.2	0.195	0.19	0.185	0.18	0.175	0.17	0.165	0.16	0.155
	2.11A.F.1.6	Mobile Air-Conditioning		Disposal loss factor	%	0.5	0.485	0.47	0.455	0.44	0.425	0.41	0.395	0.38	0.365
	2.11A.F.1.1	Domestic Refrigeration	HFC-134a	Amount of fluid in new manu	t	0	0.996711	1.896377	2.698508	50.01817	48.0975	45.14564	42.18316	39.20986	36.22555
	2.11A.F.1.1	Domestic Refrigeration	HFC-134a	Amount of fluid in operating	t	0	0	0	0	0	0	0	0	0	0
	2.11A.F.1.1	Domestic Refrigeration	HFC-134a	Amount of fluid remained in	t	0	0	0	0	0	0	0	0	0	0
	2.11A.F.1.1	Domestic Refrigeration	HFC-134a	Actual emissions from man	t	0	0	0	0	0	0	0	0	0	0
	2.11A.F.1.1	Domestic Refrigeration	HFC-134a	Actual emissions from stoc	t	0	0	0	0	0	0	0	0	0	0
	2.11A.F.1.1	Domestic Refrigeration	HFC-134a	Actual emissions from disp	t	0	0	0	0	0	0	0	0	0	0
	2.11A.F.1.2	Commercial Refrigeration	HFC-125	Amount of fluid in new manu	t	0	1.074285	2.552613	4.667191	9.164338	20.58381	48.06266	79.32604	112.6104	131.2037
	2.11A.F.1.2	Commercial Refrigeration	HFC-125	Amount of fluid in operating	t	0	0	0	0	0	0	0	0	0	0
	2.11A.F.1.2	Commercial Refrigeration	HFC-125	Amount of fluid remained in	t	0	0	0	0	0	0	0	0	0	0
	2.11A.F.1.2	Commercial Refrigeration	HFC-125	Actual emissions from man	t	0	0	0	0	0	0	0	0	0	0
	2.11A.F.1.2	Commercial Refrigeration	HFC-125	Actual emissions from stoc	t	0	0	0	0	0	0	0	0	0	0
	2.11A.F.1.2	Commercial Refrigeration	HFC-125	Actual emissions from disp	t	0	0	0	0	0	0	0	0	0	0
	2.11A.F.1.2	Commercial Refrigeration	HFC-134a	Amount of fluid in new manu	t	0	14.4739	34.33167	62.66744	100.9725	107.8269	116.9569	132.5528	148.3014	159.6693
	2.11A.F.1.2	Commercial Refrigeration	HFC-134a	Amount of fluid in operating	t	0	0	0	0	0	0	0	0	0	0
	2.11A.F.1.2	Commercial Refrigeration	HFC-134a	Amount of fluid remained in	t	0	0	0	0	0	0	0	0	0	0
	2.11A.F.1.2	Commercial Refrigeration	HFC-134a	Actual emissions from man	t	0	0	0	0	0	0	0	0	0	0
	2.11A.F.1.2	Commercial Refrigeration	HFC-134a	Actual emissions from stoc	t	0	0	0	0	0	0	0	0	0	0

3.5 Updating the Model

This section provides step-by-step "user's guide" instructions for how to make updates to the model, including how to add a chemical, how to revise end-use assumptions, and how to adjust model outputs.

3.5.1 Adding a Chemical

If a user needs to reflect that a new chemical (that is, a chemical not currently in the master list on the General Inputs sheet) is used in any end-use, that chemical needs to be added to the master chemical list in Table A on the General Inputs sheet. To do so, the user must:

4. Add the chemical name to the first empty row in the Refrigerant column in Table A on the General Inputs sheet.
    - Specify if the chemical is a CFC or HCFC in the Type column

5. Fill out the remainder of Table A and Table B, if necessary.

- ***If the new refrigerant is a blend of different chemicals***, enter its composition by percentage in the appropriate component columns (i.e. for each component listed, enter what percentage of the refrigerant it composes). If the blend includes any components that are not already listed, enter the new components in the first empty column in the "Components" row, drag over the formula in the gray row, and add that component chemical and its GWP(s) to Table B, as described below.
- ***If the new refrigerant is a neat composition***, add it to Table B and enter its GWP(s) in the yellow cells. Then add that chemical to the next empty column in the "Components" row (row 13), drag or copy over the formula in the gray row, and enter "1" in the row that you just added. The GWP should appear in the GWP column.

6. Check whether any new components are required to be reported under the UNFCCC (this will be flagged above the new component entry column, or you can consult the list next to Table B). If it is not in this list, you can skip to step 5.

7. ***If the new refrigerant or any of its components are required to be reported to the UNFCCC,*** you will need to update the structure of the CRF output generator tabs ("CRF Calculations," "CRF Outputs_formulas," and "Output for CRF").
   - On the CRF Calculations tab, you will need to add six rows for the new chemical under the appropriate end-use(s). You will only need to add the chemical under the CRF end-use where the chemical will be used.
     - Copy and paste everything from the six rows above into your new six rows (this should be rows for each CRF variable from "Amount of fluid in new manufactured products" to "Actual emissions from disposal."
     - You need to change only the values in the "Reporting Chemical" column to contain the new chemical name, and the "Model Chemical" column to contain either the new chemical name (if it is a neat chemical), or the blend it belongs to (if the new chemical required for reporting is a component of a blend).
- Unhide the CRF Outputs_formulas sheet by right-clicking on the CRF Calculations tab and clicking "Unhide..." Then select the sheet name and click "OK." The CRF Outputs_formulas tab will appear.
     - Repeat a similar process as on the CRF Calculations tab, entering six new rows under the appropriate end-use(s), copying the above set of rows, and changing only the chemical name.
     - Re-hide the sheet by right-clicking on the tab name and clicking "Hide."

8. Now that the chemical is incorporated into the model framework, you can add the assumptions about that chemical's consumption on the appropriate end-use sheet(s). On each end-use sheet, scroll down to the "Proportion of Refrigerants Used in New Equipment" table in part 4. You will see the new chemical at the bottom of the chemical list in the first column. Now enter what percentage of refrigerant in new equipment the new chemical comprises for any year.
   - If you have assumptions for any years not shaded yellow, enter those assumptions, shade the cell yellow, and then adjust the formulas in the white cells to calculate a linear trend between years for which you have assumptions.
   - Make sure that the values still sum to 100% for each year (see the Checker row at the bottom of the table, which will show a green 1.000 if this condition is met).

3.5.2 Adjusting End-Use Assumptions

Users can easily adjust assumptions on the end-use sheets. These include the end-use lifetime, whether the end-use is refilled, whether reduced leak rates apply to all existing equipment due to the EC F-gas regulation starting in 2010,[7] product charge size, loss rates, percentage imported pre-charged, market assumptions, and the proportions of refrigerants used in new equipment.

If you need to make any changes in values not in yellow cells (such as in the Inputs table in part 1 of the end-use sheet) or in the refrigerant proportions table in part 4, you will need to adjust the formulas in the white cells to calculate a linear trend between years for which assumptions are entered.

[7] The feature of reducing leak rates for existing equipment in 2010 due to the F-gas regulation is not currently applied in the model, but could be activated in future.

If you change the end-use lifetime, you will need to adjust one row of formulas in Part 4 of the end-use sheet, in the Market Data table (see Figure 13). In the Disposed Units row, the formula in the gray cells should apply to only as many columns as there are years in the lifetime, and the formula in the white cells in that row should be applied in all other columns. For example, if the lifetime is increased by two years, the formula in the gray cells should be extended two cells to the right, and if the lifetime is decreased by two years, the formula in the white cells should extended two cells to the left.

Figure 13: Updating Market Data Table if End-Use Lifetime is Changed

Activity Data

Tonnes of refrigerant in 1990 stock = 1990 Stock (units) × Charge Size (kg/unit) × 0.001 Tonnes/kg × % applied to each refrigerant
Tonnes of refrigerant used for new equipment in the UK = New Units × Charge Size (kg/unit) × 0.001 Tonnes/kg × % applied to each refrigerant

Stock Assumptions

Year	Estimate/Assumption
1990-2008	Back-cast 2010 stock based on historical GDP
2009	**85,000** refrigerated road vehicles and **500** intermodal containers (based on confidential industry estimate)
2010-2015	2% annual growth rate (based on confidential industry estimate and Honeywell 2011)
2016-2030	0.5% annual growth rate (Oko-Recherche 2011 and Honeywell 2011)
2031-2050	0% annual growth (ICF assumption)

Market Data

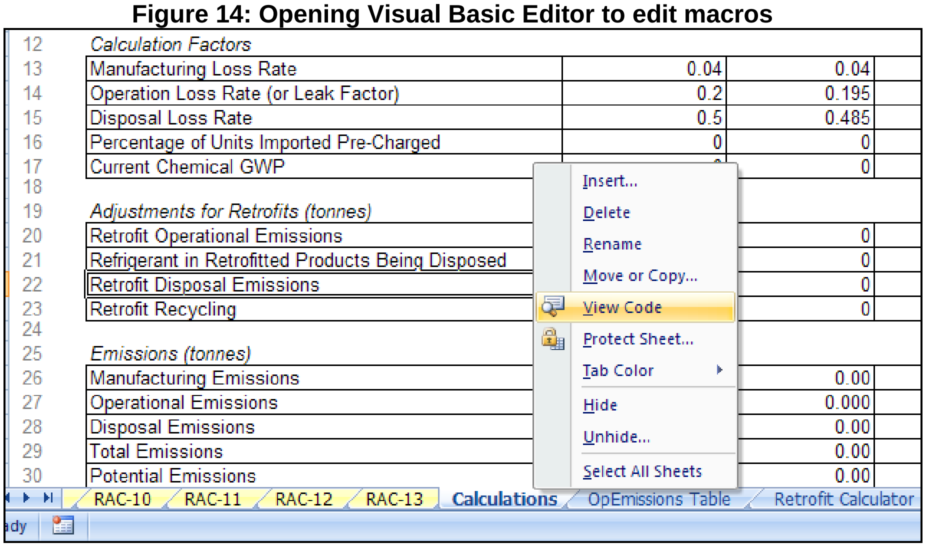
	1990	1991	1992	1993	1994	1995	1996	1997	1998
Stock	54,892	54,892	54,947	56,156	58,571	60,387	62,138	64,188	66,499
New Units	7,841.78	7,842	7,897	9,051	10,256	9,657	9,593	9,892	10,153
Disposed Units	7,841.78	7,841.78	7,841.78	7,841.78	7,841.78	7,841.78	7,841.78	7,842	7,842
Remaining from previous year		47,051	47,051	47,106	48,314	50,729	52,545	54,296	56,347
GDP Growth Rate	0.80%	0.0%	0.1%	2.2%	4.3%	3.1%	2.9%	3.3%	3.6%
Projected Growth Rate									

3.5.3 Adjusting Model Outputs

The model is capable of generating outputs for every row of the Calculations table (from the second half of the Calculations sheet). Many of these rows represent intermediate calculation steps and have not been configured to load into the model output at this time, as the model takes longer to run the more variables are processed. However, if the user wants to generate additional outputs from the calculations table, they can follow the following steps. Note that this involves opening the Macro that runs the model in Visual Basic Editor. It is recommended that users have some familiarity with the Visual Basic Editor before making such edits, as mistakes during this step can cause the model to run incorrectly.

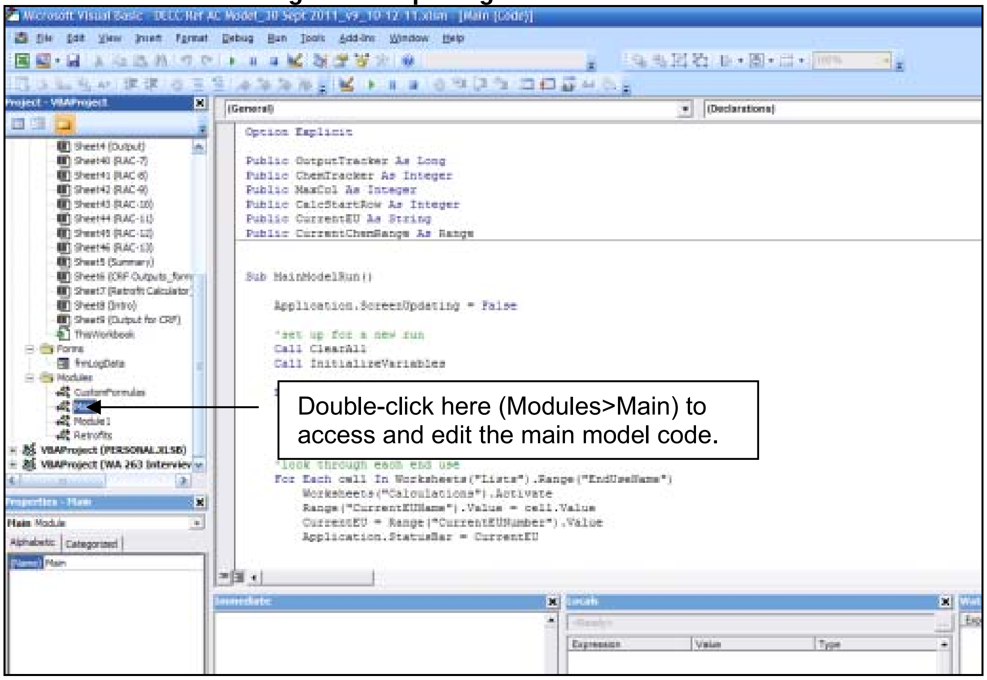
1. Right-click on the Calculations tab and select “View Code” (see Figure 14). This will pull up the Visual Basic Editor.

Figure 14: Opening Visual Basic Editor to edit macros



2. In the VBA project window on the left, you will see a list of the sheets and other components of the spreadsheet. Scroll down until you see the “Modules” folder and expand it. Then double click on “Main” (see Figure 15). This will open up the macro that runs the model.

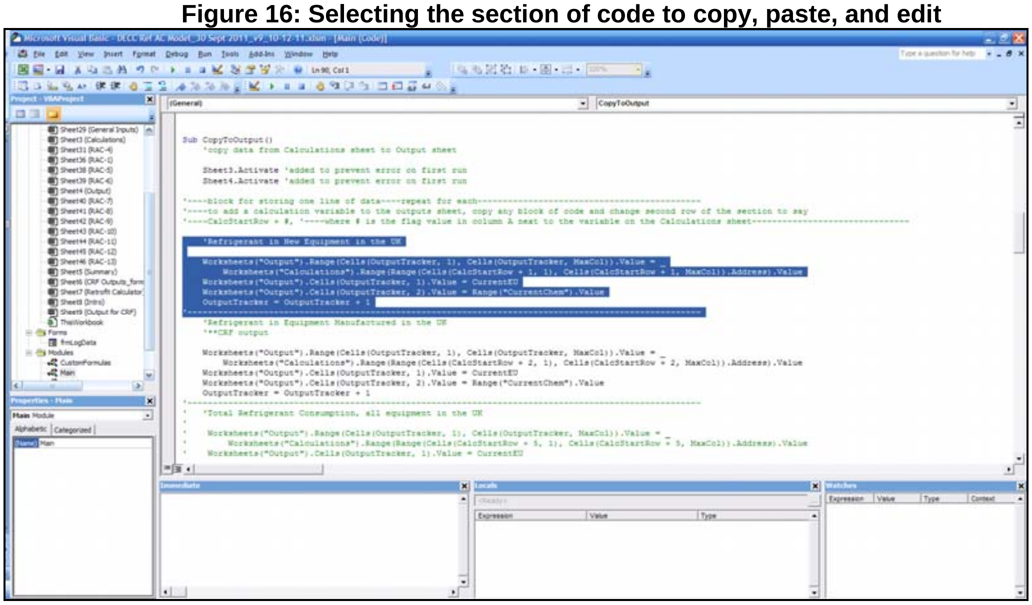
Figure 15: Opening the "Main" Module



3. Scroll down through the model code until you see “Sub CopyToOutput ( ).” You’ll notice portions of the code separated by green comment lines.

4. To add any new variable, copy a “chunk” of existing code and paste it below (see Figure 16).

Figure 16: Selecting the section of code to copy, paste, and edit



5. Re-name the section (in the green line) to the variable you want to add.

6. Edit the code in that section to refer to the appropriate variable: in the second row of the code, and change the two instances that say “CalcStartRow + #.” Change the # so that it equals the value in Column A on the Calculations sheet next to the variable you want to add. For example, the flag next to Retrofit Operational Emissions is “20”, so to add Retrofit Operational Emissions as an output variable, the second line of code should say:

```
Worksheets("Calculations").Range(Range(Cells(CalcStartRow + 20, 1),
Cells(CalcStartRow + 20, MaxCol)).Address).Value
```

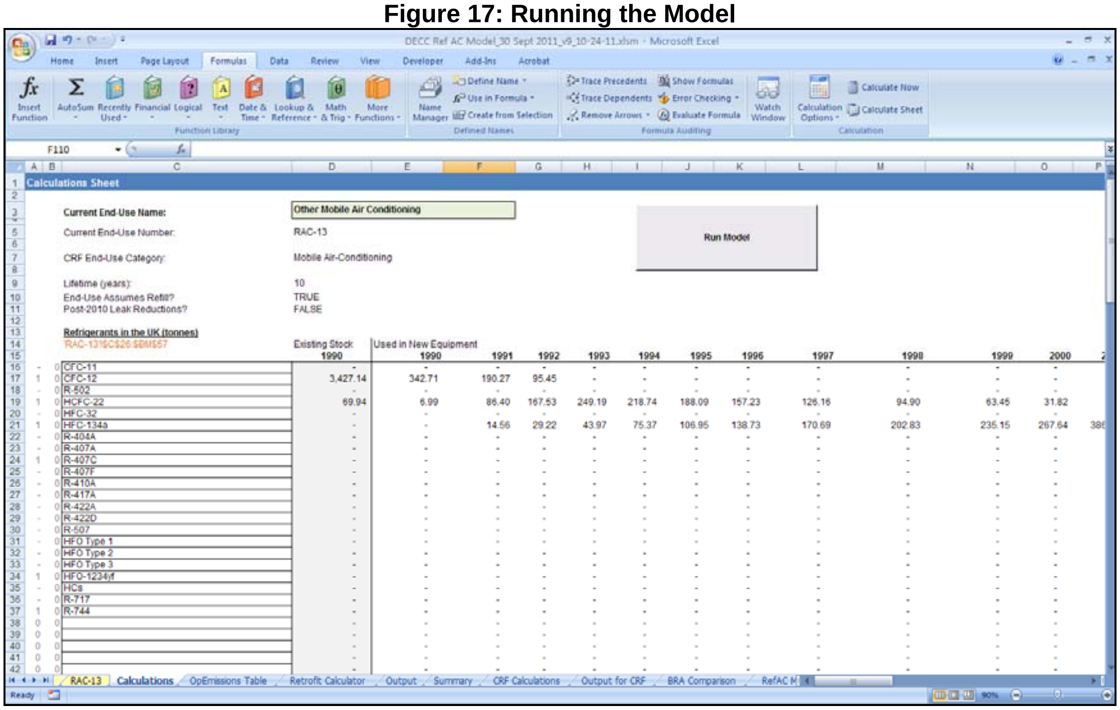
7. Save and close out of Visual Basic.

3.5.4 Running the Model

Once the user has made model updates, the model must be re-run to generate new outputs and summaries based on the new inputs. To do so:

1. Click the “Run Model” button at the top of the Calculations sheet. The model may take several minutes to run. You can follow the model’s progress by checking which end-use it is on in the bottom-left corner of your screen (see Figure 17).

Figure 17: Running the Model



2. Go to the CRF Calculations sheet and click “Generate CRF Outputs Sheet.”

3.5.5 Using the Calculations Sheet

The full set of calculations for any end-use and chemical combination can be viewed on the Calculations sheet. To do so:

1. Select the end-use from the green-shaded drop-down menu at the top the calculations sheet, “Current End-Use Name.”
2. Select the chemical you wish to view by scrolling down to the next drop-down menu, “Current Chem.”
3. Click the button “Update Retrofit Calculations for Current End-Use and Chemical” to update the calculations. Update the retrofit calculation adjustments. Go to the Retrofit Calculator sheet and click the button “Update Retrofit Calculations for Current Chemical and End-Use.”
4. Return to the Calculations sheet to view the results.

4 Summary of Model Updates by End-Use

The following section provides an overview of the end-uses as well as the input assumptions that ICF used to model the UK's refrigeration/AC sector. ICF identified13 end-uses to more accurately and transparently characterise the refrigeration/AC sector in contrast to the nine end-uses included in the previous version of the model. Table 10 summarises the end-uses previously defined in the DECC model, while Table 11 identifies and defines the new end-uses that are included in the updated model. In short, ICF added four new end-uses—heat pumps, marine transport refrigeration, medium stationary AC and other mobile AC—and more clearly defined the types of equipment included in each end-use. In particular, ICF revised definitions for commercial refrigeration equipment (i.e., small commercial stand-alone refrigeration units, condensing units, and centralised refrigeration systems) and building AC (i.e., small and medium stationary AC). ICF also disaggregated and more clearly defined the transport refrigeration and mobile AC end-uses.

Table 10. Previous Model End-Uses and Definitions

Previous Model End-Use		Description
(R1)	Domestic Refrigeration	Includes refrigerators, chest freezers, upright freezers, and fridge freezers
(R2)	Other Small Hermetic Refrigeration Units	Includes through the wall AC, retail equipment, drinking coolers, etc.
(R3)	Small Commercial Distributed Systems	Includes pub cellar coolers, small chill. and cold stores
(R4)	Supermarket Systems	None provided
(R5)	Industrial Systems	None provided
(R6)	Building Air-conditioning Systems	Direct use of refrigerant
(R7)	Building Air-conditioning Chillers	Indirect use of refrigerant
(R8)	Refrigerated Transport	Refrigerated lorries, containers, etc. using conventional refrigeration technology
(R9)	Mobile Air-conditioning	AC systems for cars and other vehicles

Table 11. Revised Model End-Uses and Definitions

Revised Model End-Use		Description
RAC-1	Domestic Refrigeration	Refrigerated appliances including refrigerators, chest freezers, upright freezers, and fridge freezers.
RAC-2	Small Commercial Stand-Alone Refrigeration Units	Small, hermetic, stand-alone refrigeration units including ice cream cabinets and drinking water coolers. These systems are commonly used in retail food stores but are also found in pubs, restaurants, and other hospitality and catering outlets such as hotels, hospitals, and schools.
RAC-3	Condensing Units	Refrigeration systems composed of one (or two) compressor(s), one condenser, and one receiver assembled into a unit, which is located external to the sales area. These units are typically installed in small shops and have refrigeration capacities ranging from 1 kW to 20 kW.
RAC-4	Centralised Refrigeration Systems	Refrigeration systems that are comprised of racks of compressors installed in a machinery room. These systems are commonly used in supermarket applications.
RAC-5	Industrial Systems	Refrigeration systems including industrial process refrigeration and cold storage.
RAC-6	Small Stationary Air Conditioning	Includes small self-contained ACs (including window units) and non-ducted split ACs. Units are used primarily in commercial applications, but there is some use in the residential sector. System cooling capacities typically range from 3 to 12 kW.
RAC-7	Medium Stationary Air Conditioning	Includes ducted split, variable refrigerant flow (VRF) non-ducted split, ducted split, and packaged AC. Units are used in the commercial UK sector. System cooling capacities typically range from 12 to 30 kW.
RAC-8	Large Stationary Air Conditioning (Chillers)	Large, indirect chillers used for commercial comfort air conditioning.
RAC-9	Heat Pumps	Residential and small commercial heat pumps, including air-source heat pumps (ASHP) (air-to-air and air-to-water systems) and ground-source heat pumps (GSHP).
RAC-10	Land Transport Refrigeration	Refrigerated road vehicles (i.e., light commercial vehicles, trucks, trailers) and intermodal containers.
RAC-11	Marine Transport Refrigeration	Refrigerated general cargo ships, container ships and fishing vessels (1,000 GT and above).
RAC-12	Light Duty Mobile Air Conditioning	AC systems for passenger cars and light commercial vehicles (up to 3.5 tonnes). Both of these vehicle types are covered under Directive 2006/40/EC (the MAC Directive).
RAC-13	Other Mobile Air Conditioning	AC systems for trucks (over 3.5 tonnes), buses/coaches, semi-trailers, trailers, and railcars.

Previous end-use assumptions (e.g., lifetime, leak rates) were developed by AEA based on industry consultations, which were not well documented and in need of updating. Moreover, because most end-uses were modelled using a top-down approach, many end-use parameters (e.g., stock, charge size) needed to be developed for the first time in order to develop new bottom-up estimates. In developing modelling input assumptions by end-use, ICF applied expert judgment to select appropriate values when more than one estimate was provided by literature and/or stakeholders. In general, more weight was given to estimates that are UK-specific and/or more recent. In cases of equal data quality where numerous data points were available, values were selected based on the mid-point of the data range. Where no UK-specific information was available, ICF relied on the 2000 Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance default assumptions to estimate emissions. The 1996 and 2006 IPCC reports were also reviewed and considered, but the latter (most recent) assumptions could not be adopted at this time without additional supporting information, per IPCC guidance. The table below summarises the default assumptions from the IPCC 2000 Good Practice Guidance.

Table 12. IPCC (2000) Default Charge Size, Lifetime, and Leak Rate Assumptions

End-Use	Charge (kg)	Lifetimes (years)	Initial Emission	Lifetime Emission	End-of-Life Emission (recovery efficiency)
Domestic Refrigeration	0.05 ≤ c ≤ 0.5	12 ≤ t ≤ 15	0.2 ≤ e ≤ 1	0.1 ≤ e ≤ 0.5	70% of remainder
Stand-alone Commercial Applications	0.2 ≤ c ≤ 6	8 ≤ t ≤ 12	0.5 ≤ e ≤ 3	1 ≤ e ≤ 10	70 ≤ r ≤ 80% of remainder
Medium & Large Commercial Refrigeration	50 ≤ c ≤ 2000	7 ≤ t ≤ 10	0.5 ≤ e ≤ 3	10 ≤ e ≤ 30	80 ≤ r ≤ 90% of remainder
Transport Refrigeration	3 ≤ c ≤ 8	6 ≤ t ≤ 9	0.2 ≤ e ≤ 1	15 ≤ e ≤ 50	70 ≤ r ≤ 80% of remainder
Industrial Refrigeration including Food Processing and Cold Storage	10 ≤ c ≤ 10K	10 ≤ t ≤ 20	0.5 ≤ e ≤ 3	7 ≤ e ≤ 25	80 ≤ r ≤ 90% of remainder
Chillers	10 ≤ c ≤ 2000	10 ≤ t ≤ 30	0.2 ≤ e ≤ 1	2 ≤ e ≤ 15	80 ≤ r ≤ 95% of remainder
Residential and Commercial A/C, including Heat Pumps	0.5 ≤ c ≤ 100	10 ≤ t ≤ 15	0.2 ≤ e ≤ 1	1 ≤ e ≤ 5	70 ≤ r ≤ 80% of remainder
Mobile Air Conditioners	0.8	12	0.5	10 ≤ e ≤ 20	40% of remainder

For each end-use identified in Table 11, research findings and updates on equipment stocks, growth rates, lifetimes, operation loss rates, charge sizes, and refrigerant transitions for all years are summarized in the following subsections. A summary table of the 2010 input assumptions are provided in Appendix B.

4.1 Domestic Refrigeration

4.1.1 Overview of Previous Model Assumptions

The domestic refrigeration end-use previously used a bottom-up approach to model HFC consumption and emissions. Stock estimates of refrigerators, fridge-freezers, chest-freezers, and upright freezers were based on the UK Market Transformation Programme (MTP 2008). HFC-134a was assumed to be the only HFC consumed in this end-use. HFC-134a first entered the market in 1993, growing to a total installed base of 1,522 MT in 2010. By 2010, only 5% of new domestic equipment was assumed to contain HFCs. Equipment was assumed to have a lifetime of 11 years. HFC charge size and leak rate assumptions for select years are summarized in Table 13 below.

Table 13. Previous HFC Refrigerant Loss Rate and Charge Size Assumptions

Input	1990	2000	2010	2050
Average HFC charge size (kg)	0.3	0.13	0.13	0.13
Manufacturing Loss Rate	1%	1%	1%	1%
Lifetime Leak Rate	1%	1%	0.3%	0.3%
Disposal Loss Rate	65%	65%	1%	1%

4.1.2 End-Use Definition

Refrigerated appliances including refrigerators, chest freezers, upright freezers, and fridge freezers.

4.1.3 Summary of Research Findings and Updates

Equipment Stocks and Growth Rate

Stock Data

Stock data from the UK Market Transformation Programme (MTP 2010) was used to determine the equipment stock and annual sales for this end-use. Actual and projected stock data are available for the years 2000-2030. Additionally, the most recent information available from the Office of National Statistics (2007) was used to identify the quantity produced domestically vs. imported. Based on this information, 90% of units are assumed to be manufactured pre-charged outside of the UK.

Market Growth Rates

Stock data from the UK Market Transformation Programme (MTP 2010) is provided for the years 2000-2030, implying an annual average market growth rate of 1.2% from 2000-2010, and of 0.9% from 2010-2030. Similarly, EC (2010) projects EU growth rates of 1% (2009-2020) and 0.5% (2020-2050), based on average historical growth rates from the LOT 13: Domestic Refrigerators and Freezers Final Report (ISIS, 2007). ICF used the stock data from MTP to calculate market growth through 2030. The 2000-2010 average annual growth rate of 1.2% was used to estimate stock data from 1990-2000. Post-2030, ICF assumes no market growth.

Equipment Lifetime

According to MTP (2010), the average equipment lifetime of refrigerators/freezers in the UK is 15 years. Both Oko-Recherche et al. (2011) and EC (2010) also assume a product lifetime of 15 years. IPCC (2000) assumes a default lifetime of 12 to 15 years while IPCC (2006) assumes a default lifetime of 12 to 20 years. Although the previous model assumed a lifetime of 11 years, no data sources reviewed supported this assumption. Therefore, ICF increased the lifetime to 15 years.

Refrigerant Use and Transitions

HFC-134a is the only HFC used in domestic refrigerators and first entered the market in 1993. HFC-134a dominated the European market in the late 1990s but has largely been displaced in new equipment by HCs (Oko-Recherche et al. 2011). According to RTOC (2010), in 1996 65% of newly produced units in Western

Europe contained HFC-134a while the remaining 35% contained HCs; by 2008, the percent of newly produced units containing HFC-134a dropped to 16%. Today in the UK, refrigerators containing HCs represent about 50% of units reaching end-of-life (Overton Recycling 2011). Globally, the first HC units were produced in 1993 (CGE 2011) but it is estimated that they did not penetrate the UK market until 2000 (Gluckman 2011). As a result, ICF assumes the following market penetrations of refrigerants in new domestic refrigerators sold in the UK for key years.

Table 14. Revised Market Penetration of Refrigerants into New Domestic Refrigerators*

Year	12	134a	HCs (R-600a)
1990	100%	-	-
1993	95%	5%	-
1994	2%	98%	-
1995-1999	-	100%	-
2000	-	95%	5%
2005	-	50%	50%
2010-2020	-	5%	95%
2021-2050	-	-	100%

* For years not listed, a linear change between identified years is assumed.

HFC Charge Size and Loss Rates

HFC Charge Size

According to RTOC (2010), global domestic refrigerators typically contain 0.05-0.25 kg of refrigerant. Oko-Recherche et al. (2011) estimate an average charge of 0.12 kg in the EU. IPCC (1996) does not provide charge size estimates for domestic refrigerators, but IPCC (2006) and IPCC (2000) estimates that domestic refrigerators have a charge size that ranges from 0.05 – 0.5 kg. Overton Recycling (2011) indicates that UK domestic refrigerators contain roughly 100 g of refrigerant. This information is summarised in the table below.

Table 15. Summary of Charge Size Estimates for Domestic Refrigerators

Source	Charge Size Estimate (kg)
IPCC (2000)	0.05 – 0.50
IPCC (2006)	0.05 – 0.50
Oko-Recherche et al. (2011)	0.12
Overton Recycling (2011)	0.1
RTOC (2010)	0.05 – 0.25

Based on this information, ICF assumes an average charge size of 0.10 kg today and in the future, with slightly higher charge sizes in earlier years (i.e., 0.13 kg in 2000 and 0.25 kg in 1990) to account for technological changes over time. This is at the lower end of the IPCC default range, but is considered to be appropriate for the UK because it is supported by UK specific data (from Overton Recycling), as well as EU-specific data (from Oko-Recherche et al.).

Manufacturing Loss Rate

IPCC (2006) and IPCC (2000) estimate that initial emissions from domestic refrigeration equipment are between 0.2% and 1%, while IPCC (1996) estimates assembly losses are 2% of the total charge. Oko-Recherche et al. (2011) similarly assume a manufacturing loss rate in the EU of 0.6%. ICF updated the previous manufacturing loss rate of 1% to 0.6%, based on the EU-specific estimate provided in Oko-Recherche et al. (2011).

Operational Loss Rate

Oko-Recherche et al. (2011) assume an equipment leak rate of 0.3%. IPCC (1996) assumes an annual leak rate of 1%, while IPCC (2006) and IPCC (2000) assume a range of 0.1% to 0.5%. Recognising that some leakage will occur, albeit very small, and that a small percentage of systems will suffer catastrophic damage, ICF maintained the previous lifetime loss rate of 0.3%, which is in line with Oko-Recherche et al. (2011) and within the range provided by IPCC (2006) and IPCC (2000). ICF assumes a historic leak rate of 1%, consistent with the previous model's estimate and a constant leak rate of 0.3% in the future, based on the assumption that the leak tightness technology for domestic refrigerators will not change significantly in the future (Gluckman 2011). ICF also assumes that no servicing occurs; i.e., the amount of refrigerant in each unit decreases over time due to annual leaks.

Disposal Loss Rate

Oko-Recherche et al. (2011) assume a disposal loss rate of 40%. Similarly, IPCC (1996) implies a disposal loss rate of 45% (90% of the charge remains at disposal and 50% of the remaining charge is recovered). IPCC (2000) estimates that 70% of the remaining charge is recoverable at end-of-life (EOL). IPCC (2006) implies a disposal loss rate of 0-24% or more (recovery efficiency of up to 70% and with 0-80% of charge remaining). EC (2010) assumes that 90% of what remains in equipment at EOL is technically recoverable in the EU-15. According to one industry representative in the disposal sector, the vast majority (≥98%) of disposed household refrigerators/freezers are properly handled, and roughly 50 g of refrigerant—or roughly 50% of the original charge—is recoverable from units at EOL (Overton Recycling 2011). This implies that at most 50% is emitted prior to or during disposal. This information is summarised in the table below.

Table 16. Summary of Available Disposal Loss Estimates for Domestic Refrigerators

Source	Percent of Original Charge Remaining at EOL	Recovery Efficiency (% of remaining charge that can be recovered)	Estimated Disposal Loss (as % of original charge)
EC (2010)	NA	90%	≤10%
IPCC (1996)	90%	50%	≥45%
IPCC (2000)	NA	70%	≤30%
IPCC (2006)	0-80%	70%	≥0-24%
Oko-Recherche et al. (2011)	NA	NA	40%
Overton Recycling (2011)	NA	NA	≤50%

Based on this information, ICF updated the disposal loss rate of 1% to 35% in 2010, and decreased it to 30% by 2020 and 25% by 2030. The updated disposal loss rates are in the range of the estimates identified by the literature/industry (i.e., 0%-50%) and are higher than the previous estimates to account for losses that occur during equipment transport and handling, during the recovery process itself, as well as potential non-compliance with refrigerant recovery requirements. While this rate is higher than the percentage noted in IPCC (2000), the IPCC estimate speaks to what is *technically* recoverable, without considering actual recovery practices/compliance rates in-country. These higher estimates were further vetted by industry, who agreed that the higher disposal loss rate figures were much more realistic (Gluckman 2011). The disposal loss rate for earlier years (1990-2000) was maintained based on the assumption that recovery practices and technologies have improved over time, in response to regulatory requirements and enhanced compliance.

Summary

The table below summarises the revised assumptions related to HFC charge size and loss rates.

Table 17. Summary of Revised Charge Size and Loss Rate Assumptions for Domestic Refrigerators*

Input	1990	2000	2010	2020	2030-2050
Average HFC Charge Size (kg)	0.25	0.13	0.10	0.10	0.10
Manufacturing Loss Rate	0.6%	0.6%	0.6%	0.6%	0.6%
Operational Leak Rate	1%	1%	0.3%	0.3%	0.3%
Disposal Loss Rate	65%	40%	35%	30%	25%

*For years not listed, a linear change in market penetration between identified years is assumed.

4.1.4 Summary of Model Updates

The table below summarises the model updates described above for an indicative list of parameters.

Table 18. Comparison of Previous vs. Revised Assumptions for Key Parameters

Input	Previous	Revised
Average HFC charge size (kg) for equipment built in 2010	0.13	0.10
Manufacturing Loss Rate (2010)	1%	0.6%

Operational Leak Rate (2010)	0.3%	0.3%
Disposal Loss Rate (2010)	1%	35%
Lifetime (years)	11	15

4.1.5 References

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4.2 Small Hermetic Stand-Alone Refrigeration Units

4.2.1 Overview of Previous Model Assumptions

The "other small hermetic refrigeration units" end-use previously used a top-down approach to model HFC consumption and emissions. HFCs were assumed to first enter the market in 1994, growing to a total installed base of 328 MT in 2010. Assumptions for the penetration of HFCs entering the market in new or retrofit equipment are summarized below.

Table 19. Previous Market Penetrations of HFC Refrigerants into New/Retrofitted Units

	134a	404A	407C	410A	417A*	507
1990	90%	5%	3%	-	-	2%
2003	40%	25%	24%	10%	1%	-
2007	35%	20%	20%	22%	3%	-
2008 - 2050	20%	10%	5%	65%	-	-

* R417A is used to convert R-22 equipment.

In the previous model, equipment was assumed to have a lifetime of 5 years. HFC refrigerant loss rate assumptions for select years are summarized in the table below.

Table 20. Previous HFC Refrigerant Loss Rate Assumptions

Input	1990	2000	2010	2050
Manufacturing Loss Rate	1%	1%	1%	1%
Lifetime Leak Rate	5%	5%	1%	1%
Disposal Loss Rate	50%	50%	5%	3%

4.2.2 End-Use Definition

Small, hermetic, stand-alone refrigeration units including ice cream cabinets and drinking water coolers. These systems are commonly used in retail food stores but are also found in pubs, restaurants, and other hospitality and catering outlets such as hotels, hospitals, and schools.

4.2.3 Summary of Research Findings and Updates

Equipment Stocks and Growth Rate

Stock Data

Stocks of small stand-alone refrigeration units were estimated based on the number of food retail, hospitality, and catering outlets in the UK. According to IGD (2010), there were 91,509 grocery stores in the UK in 2010—including convenience stores, traditional food retail stores, and supermarkets. A study published by the British Hospitality Association (2009) estimates that there were approximately 263,000 hospitality and catering outlets in the UK in 2008, covering both the profit sector (which includes hotels, restaurants, quick-service outlets, pubs, and leisure venues) and the cost sector comprising catering in business and industry, healthcare, education, and Ministry of Defence sites. Table 21 summarises the estimated number of stand-alone units in the UK based on the number of establishments and assumptions regarding units per establishment. Assumptions regarding units per establishment were estimated based on industry input (Gluckman 2011) and consideration of other published sources (Armines 2009, EC 2010).

Table 21. Estimated Number of Stand-Alone Units Currently in the UK

Sector	Number of Outlets	Estimated Number of Stand-Alone Units per Outlet[c]	Estimated Number of Stand-Alone Units
Convenience Stores	48,289[a]	7	338,023
Traditional Food Retail Stores	35,250[a]	10	352,500
Supermarkets	7,970[a]	15	119,550
Hotels	46,019[b]	5	230,095

Sector	Number of Outlets	Estimated Number of Stand-Alone Units per Outlet[c]	Estimated Number of Stand-Alone Units
Restaurants	27,153[b]	5	135,765
Quick Service	30,716[b]	5	153,580
Pubs	49,343[b]	7	345,401
Leisure	19,409[b]	5	97,045
Business & Industry	20,158[b]	5	100,790
Healthcare	31,770[b]	10	317,700
Education	34,482[b]	5	172,410
Ministry of Defence	3,084[b]	5	15,420
TOTAL	**353,643**	**-**	**2,378,279**

[a] IGD (2010).
[b] British Hospitality Association (2009).
[c] ICF estimates based on Gluckman (2011), Armines (2009), and EC (2010).

To assess whether the above bottom-up estimates are reasonable, rough UK estimates were developed based on global estimates provided in TEAP (2009) and EU-specific estimates provided in Oko-Recherche et al. (2011) for the sake of comparison. TEAP (2009) estimates there are 32 million stand-alone units in operation globally; this would correspond to approximately 1.14 million stand-alone units in the UK, if scaled based on World Bank (2011) GDP data. Oko-Recherche et al. (2011) estimate there are 52.5 million units in developed countries; this translates to roughly 3 million stand-alone units in the UK, if scaled based on World Bank (2011) GDP data. Because the above bottom-up estimates fit squarely within this range (of 1.1 to 3 million), they are deemed to be reasonable. Accordingly, ICF assumes 2.4 million stand-alone units in the UK in 2010.

Market Growth Rates

The UK grocery retail market size has steadily increased since 1999. Since 2005, grocery market performance in the UK has increased through 2008, but decreased through 2010, largely due to the recession (IGD 2010).

EC (2010) estimates a 3% growth rate from 2010-2020 for stand-alone units in the EU-15, and a growth rate of 1.5% from 2020-2050. Oko-Recherche et al. (2011) estimate 2-4% growth from 2010-2020 in the EU, and then 2% annual growth until 2030.

Based on this information, ICF assumes a market growth rate of 3% from 2010-2020, 1.5% from 2020-2030, and 0% from 2030-2050. For 1990-2010, historic GDP data from the World Bank (2011) were used to back-cast stock estimates, with any negative growth zeroed-out (given that the recent economic downturn is not believed to have impacted this sector to the same extent as the consumer goods sectors).

Equipment Lifetime

Oko-Recherche et al. (2011) estimates a 10-year lifetime for stand-alone units, while EC (2010) estimates a 12-year lifetime, and RTOC (2010) estimates a lifetime of at least 10 years. The IPCC (2006) default lifetime is between 10 and 15 years, while the IPCC (2000) default lifetime is between 8 and 12 years. According to one UK industry estimate, average equipment life is roughly 10 years (Gluckman 2011). Based on this information, ICF increased the assumed lifetime from 5 to 10 years. This estimate is consistent with the most recent EU-specific estimate (provided by Oko-Recherche et al. 2011) and is within the range of the IPCC and RTOC values.

Refrigerant Use and Transitions

According to Honeywell (2011a), CFC-12 and R-502 were historically used in this application, followed by HCFC-22. HFCs entered the market in the mid-1990s—primarily HFC-134a, but also R404A and R407C. RTOC (2010) similarly indicates that today the market is dominated by HFC-134a, with hydrocarbons (HCs) accounting for a small but increasing share. Oko-Recherche et al. (2011) estimate that the current EU market—i.e., new sales—is dominated by R-404A (49%) and HFC-134a (49%), with the remaining 2% being HCs. Conversely, Gluckman (2011) suggests that the current UK market is more heavily dominated by R-134a relative to other HFCs.

While the previous model assumed that HCFC-22 equipment was retrofitted to R-417A in the 1990s, ICF believes that such retrofits were unlikely, given the small charge size and low servicing needs of this equipment. This assumption was not countered by industry stakeholders.

In the future, CO_2 and HFOs (e.g., HFO-1234yf, HFO-1234ze) are expected to be adopted as low-GWP alternatives. Specifically, RTOC (2010) indicates that HCs and R-744 (CO_2) are already gaining a significant market share in stand-alone units in Europe. By 2030, Oko-Recherche et al. (2011) estimate that alternatives (e.g., isobutene, propane) will make up 40% of the EU refrigerant market, and R-404A and HFC-134a will have fallen to 30% each. According to one manufacturer of HC equipment (EarthCare 2011), there is now an emerging trend towards HC units in lieu of HFC-134a, with HCs already prevalent in the commercial UK refrigeration market, and CO_2 likely to become a player in future. Similarly, one UK industry representative in the supermarket sector indicated that HCs and CO_2 will be the likely alternatives, with HFOs playing a smaller role (Marks and Spencer 2011). However, other industry stakeholders do not believe CO_2 will become technically or economically viable for use in this end-use (Honeywell 2011b, JTL Systems 2011). Honeywell (2011b) predicts that HFOs and HCs will dominate the market by 2030, accounting for 55% and 40%, respectively.

Based on this information, ICF assumes the market penetrations of refrigerants in new units sold in the UK as shown in the table below.

Table 22. Revised Market Penetration of Refrigerants into New Stand-Alone Units*

Year	12	502	22	134a	404A	407C	HFOs	HCs	744
1990	75%	15%	10%	-	-	-	-	-	-
1994	5%	-	40%	45%	5%	5%	-	-	-
1995	-	-	30%	50%	10%	10%	-	-	-
2000	-	-	10%	60%	20%	10%	-	-	-
2001	-	-	-	70%	20%	10%	-	-	-
2010	-	-	-	65%	15%	10%	-	10%	-
2015	-	-	-	60%	-	-	5%	35%	-
2020	-	-	-	25%	-	-	20%	55%	-
2030	-	-	-	-	-	-	40%	55%	5%
2050	-	-	-	-	-	-	40%	55%	5%

* For years not listed, a linear change in market penetration between identified years is assumed.

HFC Charge Size and Loss Rates

Charge Size

Oko-Recherche et al. (2011) estimates an average charge size of 0.4 kg, which could range from 0.1 to 1 kg. RTOC (2010) estimates a charge of 220 grams to 3 kg (RTOC 2010), while EC (2010) estimates 2-3 kg, TEAP (2009) estimates 150 grams to 1 kg. The IPCC (2006) and IPCC (2000) default charge size range is 0.2-6.0 kg. IPCC (1996) does not specifically define a charge size for stand-alone refrigeration units but provides a default value of 0.1-0.5 kg for commercial and industrial appliances. Estimates from literature are summarised in the table below.

Table 23. Summary of Charge Size Estimates for Stand-Alone Units

Source	Charge Size Estimate (kg)
EC (2010)	2 – 3
IPCC (2006)	0.2 – 6.0
IPCC (2000)	0.2 – 6.0
IPCC (1996)	0.1 – 0.5
Oko-Recherche et al. (2011)	0.1 – 1
RTOC (2010)	0.22 – 3.0
TEAP (2009)	0.15 – 1.0

Relying most heavily on the most recent EU-specific estimate provided by Oko-Recherche et al. (2011), ICF assumes an average HFC charge size of 0.5 kg today, and 0.75 kg in earlier years. The higher charge size in earlier years is assumed to account for technological changes over time.

Manufacture Loss Rate

The IPCC (2006) and IPCC (2000) estimate a manufacturing loss rate between 0.5% and 3% for stand-alone refrigeration units. IPCC (1996) does not specifically identify a manufacturing loss rate for stand-alone refrigeration units but identifies a default assembly loss rate for factory built equipment under the broad category of "other stationary refrigeration and air conditioning equipment" as 2-3%. Honeywell (2011b) estimates that the manufacturing loss rate today is closer to 0.5% due to improvements in charging equipment. Based on this information, ICF updated the manufacturing loss rate from 1% to 2% from 1990-2000 but kept the manufacturing loss rate at 1% beginning in 2010.

Operational Loss Rate

Oko-Recherche et al. (2011) assume a leak rate of 1%. IPCC (2006) estimates a default leak rate of 1-15% while IPCC (2000) estimates a default leak rate of 1-10%. IPCC (1996) does not specifically identify an annual leak rate for stand-alone refrigeration units but provides an operational leak rate for the broad category of "other stationary refrigeration and air conditioning equipment" of 3-17%. Recognising that some leakage will occur, albeit very small, and that a small percentage of systems will suffer catastrophic damage, ICF increased the previous assumption of 1% to 1.5% in 2010, decreasing it to 1% by 2020. ICF assumes higher loss rates in earlier years—i.e., 3% in 1990 and 2% in 2000—based on the assumption that leak tightness technology has improved over time. Loss rates towards the lower end of the IPCC (2000) range have been selected, since this is more in line with the EU specific estimates from Oko-Recherche et al. (2011). For this end-use, ICF also assumes that no servicing occurs; i.e., the amount of refrigerant in each unit decreases over time due to annual leaks.

Disposal Loss Rate

Oko-Recherche et al. (2011) estimate the disposal loss rate for hermetic units to be approximately 70% (which will decrease to 35% by 2050). EC (2010) estimates that 90% of refrigerant is remaining at EOL, of which 90% is technically recoverable; thus, the disposal loss emissions are estimated at 9% or greater, depending on recovery compliance levels. IPCC (1996) estimates that 90% of the charge remains at disposal for the broad category of other stationary refrigeration and air conditioning equipment while 80% is recovered if recovery practices are used; thus implying a disposal loss rate of at least 18%. IPCC (2006) implies a disposal loss rate of 0-24% or more (recovery efficiency of up to 70% and with 0-80% of charge remaining). IPCC (2000) estimates that 70-80% of the remaining charge is recoverable at EOL. According to one industry expert in the disposal sector (Overton Recycling 2011), roughly 100-125 g of refrigerant is typically recoverable from vending machines at disposal—or roughly 75% of the original charge. This implies that at most 25% is emitted prior to or during disposal. This information is summarised in the table below.

Table 24. Summary of Available Disposal Loss Estimates for Stand-Alone Units

Source	Percent of Original Charge Remaining at EOL	Recovery Efficiency (% of remaining charge that can be recovered)	Estimated Disposal Loss (as % of original charge)
EC (2010)	90%	90%	≥9%
IPCC (1996)	90%	80%	≥18%
IPCC (2000)	NA	70-80%	≤20-30%
IPCC (2006)	0-80%	70%	≥0-24%
Oko-Recherche et al. (2011)	NA	NA	70% today; 35% by 2050
Overton Recycling (2011)	NA	NA	≤25%

Based on the above information, ICF increased the previous disposal loss rate in 2010 from 5% to 40%. The higher rate accounts for losses that occur during equipment transport and handling, during the recovery process itself, as well as potential non-compliance with refrigerant recovery requirements. The 40% estimate is within the range of the estimates identified by the literature/industry (i.e., 0%-70%) and was further vetted by industry, who agreed that the higher disposal loss rate figure was much more realistic (Gluckman 2011). While this rate is higher than the percentages noted in four sources—i.e., EC (2010), IPCC (2000), IPCC (2006), Overton Recycling (2011)—such percentages speak to what is *technically* recoverable, without considering actual recovery practices/compliance rates in-country. For earlier years, prior to the implementation and widespread compliance with refrigerant recovery regulations in the UK, ICF assumes a disposal loss of 65% in 1990, which will decrease to 45% in 2000. For future, ICF decreases the loss rate to reach 35% by 2020 and 30% by 2030, in order to account for improvements in recovery compliance and best practices, as well as recovery technology.

Summary

The table below summarises the revised assumptions related to HFC charge size and loss rates.

Table 25. Summary of Revised Charge Size and Loss Rate Assumptions for Stand-Alone Units*

Input	1990	2000	2010	2020	2030-2050
Average HFC Charge Size (kg)	0.75	0.75	0.5	0.5	0.5
Manufacturing Loss Rate	2%	2%	1%	1%	1%
Operational Leak Rate	3%	2%	1.5%	1%	1%
Disposal Loss Rate	65%	45%	40%	35%	30%

* For years not listed, a linear change in market penetration between identified years is assumed.

4.2.4 Summary of Model Updates

The table below summarises the model updates described above for an indicative list of parameters, based on the research conducted.

Table 26. Comparison of Previous vs. Revised Assumptions for Key Parameters

Input	Previous	Revised
Average HFC charge size (kg) for equipment built in 2010	NA	0.5
Manufacturing Loss Rate (2010)	1%	1%
Operational Leak Rate (2010)	1%	1.5%
Disposal Loss Rate (2010)	5%	40%
Lifetime (years)	5	10

4.2.5 References

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4.3 Condensing Units

4.3.1 Overview of Previous Model Assumptions

The small commercial distributed systems end-use previously used a top down approach to model HFC consumption and emissions. HFCs were assumed to first enter the market in 1993, growing to a total installed base of 1,700 MT in 2010. Assumptions for the penetration of HFCs in new or retrofit equipment are summarized below.

Table 27. Previous Market Penetrations of HFC Refrigerants into New/Retrofitted Units

	134a	404A	407C	413A	417A*	422D*	507
1990	63%	20%	15%	-	-	-	2%
2003	29%	65%	1%	4%	1%	-	-
2007	28%	65%	1%	2%	2%	1%	1%
2008 - 2050	20%	79%	-	-	-	-	1%

* R-417A and R-422D are used to convert HCFC-22 equipment

In the previous model, equipment was assumed to have a lifetime of 14 years. HFC refrigerant loss rate assumptions for select years are summarized in Table 28 below.

Table 28. Previous HFC Refrigerant Loss Rate Assumptions

Input	1990	2000	2010	2050
Manufacturing Loss Rate	3%	3%	2%	2%
Lifetime Leak Rate	30%	13%	3%	3%
Disposal Loss Rate	10%	8%	5%	5%

4.3.2 End-Use Definition

Refrigeration systems composed of one (or two) compressor(s), one condenser, and one receiver assembled into a unit, which is located external to the sales area. These units are typically installed in small shops and have refrigeration capacities ranging from 1 kW to 20 kW.

4.3.3 Summary of Research Findings and Updates

Equipment Stocks and Growth Rate

Stock Data

Globally, an estimated 34 million condensing units are in use with a larger percent being used in developing countries (RTOC 2010). According to Oko-Recherche et al. (2011), 14 million condensing units are in use in A2 countries today while 1-3 million condensing units were in operation in the EU in 2006.[8]

ICF scaled the stock estimates to the UK based on GDP. Based on data from the World Bank (2011), in 2010 the UK's GDP represented roughly 14% of the EU-27, and 5% of all A2 countries. Based on this information, ICF estimated there were roughly 138,000 - 414,000 condensing units in the UK in 2006 (based on Oko-Recherche et al.), and 742,000 in 2010 (based on RTOC). In consideration of these estimates, ICF assumes that 600,000 condensing units are in operation in 2010.

Market Growth Rates

EC (2010) estimates a 3% growth rate from 2010-2020 for condensing units in the EU-15, and a growth rate of 1.5% from 2020-2050. According to Oko-Recherche et al. (2011), growth rate assumptions are similarly assumed to be 1.5% for 2010-2030. Based on this information, ICF assumes a growth rate of 1.5% for 2010-2030 and 0% growth beyond 2030. For 1990-2009, historic GDP data from the World Bank (2011) is used

[8] Oko-Recherche et al. (2011) cites the number of condensing units as both 1 million and 3 million in different places in the document. It is assumed that one of the numbers is incorrect yet a full list of references is not provided so the correct number cannot be confirmed at this time. As a result, the potential range is provided.

to back-cast stock estimates, with any negative growth zeroed-out (given that the recent economic downturn is not believed to have impacted the refrigeration sector to the same extent as the consumer goods sectors).

Equipment Lifetime

IPCC (2006) estimates a unit lifetime of 7-15 years for medium and large commercial refrigeration while IPCC (2000) estimates a lifetime of 7-10 years. Oko-Recherche et al. (2011) assume a lifetime of 15 years and EC (2010) assumes a lifetime of 12 years. Based on this information, ICF maintains the previous lifetime assumption of 14 years. This is outside of the range given by IPCC (2000), but is considered to be representative for the UK because it is the average estimate supported by EU-specific estimates (fromOko-Recherche and EC).

Refrigerant Use and Transitions

Following the phase-out of CFCs in the early 1990s, HCFC-22 was the dominant refrigerant used in condensing unit systems in developed countries. HFCs gradually began to penetrate the market in the mid-1990s (with HFC-134a becoming available in limited quantities in 1994 and HFC blends becoming available shortly thereafter), leading to the complete phase-out of HCFC-22 in new equipment by 2001. In anticipation of an HCFC-22 scarcity beginning in 2010, some HCFC-22 equipment was retrofitted to R-422D (Honeywell 2011, HARP 2011). According to Honeywell (2011), R-417A has also been used as a retrofit refrigerant. Retrofit activity peaked in 2010 but is likely to spike again in 2014, prior to the complete phaseout of HCFC-22 in the EU.

Currently, R-404A dominates the market, although it is becoming much less desirable in the UK as the push to low-GWP refrigerants intensifies across the retail food industry, resulting in growing market penetration of HFC-134a, which has a significantly lower GWP (RTOC 2010, Oko-Recherche et al. 2011, Honeywell 2011). However, according to HARP (2011), HFC-134a is not a significant player in this end-use in the UK today. EPEE (2011) indicates that R-410A is used in refrigeration condensing units today, while HFC-32 may enter the market in the near future. Mark's and Spencer (2011) also noted that use of R-404A in the UK is rapidly dropping off as the industry transitions to other refrigerants such as R-407A and R-407F.

According to Honeywell (2011), many retrofits have also been performed by major UK retailers to switch from R-404A to lower GWP HFCs, namely R-407F. However, according to HARP (2011), retrofit activity in the UK has been rather minimal and has gone to R-422D, with no significant amounts to R-417A or R-407F.

Moving forward, Gluckman (2011) anticipates the replacement of R-404A with medium GWP HFCs (i.e., HFC-134a, R-407F), HFOs, or natural refrigerants in the retail food sector in the coming years. By 2030, Oko-Recherche et al. (2011) project that 30% of new equipment in the EU will contain alternative refrigerants. By 2050, EC (2010) projects that half of the EU-15 market will be using alternative refrigerants. JTL Systems (2011) is dubious about the future use of CO_2 in condensing units. Both JTL Systems (2011) and SKM Enviros (2011) don't expect HCs to be used widely in condensing units due to flammability and safety concerns.

Based on this information, the tables below summarise the revised market penetrations of refrigerants into new and retrofitted condensing units for key years. The percentages in the latter table represent the portion of original refrigerant remaining in eligible equipment (i.e., equipment with 25-75% of its useful life remaining) that is replaced by a retrofit refrigerant.

Table 29. Revised Market Penetrations of Refrigerants into New Condensing Units*

Year	12	502	22	134a	404A	407A	407F	410A	32	507	HFOs	HCs	744
1990	30%	30%	40%	-	-	-	-	-	-	-	-	-	-
1994	5%	5%	85%	5%	-	-	-	-	-	-	-	-	-
1995	-	-	90%	8%	2%	-	-	-	-	-	-	-	-
2000	-	-	10%	8%	77%	-	-	-	-	5%	-	-	-
2001	-	-	-	8%	87%	-	-	1%	-	4%	-	-	-
2008	-	-	-	5%	87%	-	-	5%	-	3%	-	-	-
2010	-	-	-	8%	80%	2%	1%	6%	-	2%	-	1%	-
2020	-	-	-	10%	10%	15%	15%	5%	5%	-	30%	5%	5%
2030	-	-	-	5%	-		-	-	20%	-	65%	5%	5%
2050	-	-	-	-	-		-	-	20%	-	65%	8%	7%

* A linear change between identified years is assumed.

Table 30. Revised Market Penetrations of Retrofit Refrigerants into Existing Eligible Equipment*

Original	Retrofit	1990–1999	2000	2001	2005	2009	2010	2012	2014	2015	2020	2030-2050
12	22	-	100%	-	-	-	-	-	-	-	-	-
502	22	-	100%	-	-	-	-	-	-	-	-	-
22	417A/422D**	-	-	-	-	1%	30%	2%	10%	5%	-	-
404A	407A/407F**	-	-	-	-	-	1%	2%	3%	3%	2%	-

* Eligible equipment for this end-use is defined as equipment with 25-75% of its useful life remaining. Figures were developed based on confidential business information supplied by Honeywell (2011) and are expressed as a percent of total metric tonnes of the remaining original refrigerant installed in existing eligible equipment. A linear change between identified years is assumed.

** For modelling purposes, the GWP of R-422D and R-407F are used for retrofits of HCFC-22 and R-404A equipment, respectively.

HFC Charge Size and Loss Rates

HFC Charge Size

According to RTOC (2010), condensing units typically contain 1-5 kg of refrigerant. EC (2010) estimates a typical charge of 2-3 kg while Oko-Recherche et al. (2011) estimate an average charge of 8 kg. The IPCC (2006) and IPCC (2000) default charge size range for medium and large commercial refrigeration is 50-2,000 kg. Similarly, IPCC (1996) does not specifically define a charge size for condensing units but provides a default value 10-230 kg for all retail food refrigeration equipment. This information is summarized in the table below.

Table 31. Summary of Charge Size Estimates for Condensing Units

Source	Charge Size Estimate (kg)
EC (2010)	2 – 3
IPCC (2006)	50 – 2,000[a]
IPCC (2000)	50 – 2,000[a]
IPCC (1996)	10 – 230[a]
Oko-Recherche et al. (2011)	8
RTOC (2010)	1 – 5

[a] Estimate not specific to condensing units.

Based on the average of the EU-specific estimates (i.e., 2- 8 kg based on EC 2010 and Oko-Recherche et al. 2011), ICF assumes an HFC charge size of 5 kg across all years. This estimate is also within the upper bound of the RTOC (2010) estimate. UK industry representatives consulted during the research had no objections to this assumption. This is outside of the default range from IPCC (2000) and IPCC (1996), but these ranges are not specific to condensing units, or to the EU.

Manufacturing Loss Rate

IPCC (2006) and IPCC (2000) estimate that initial emissions from medium and large commercial refrigeration are between 0.5% and 3%. IPCC (1996) does not specifically identify a manufacturing loss rate for condensing units but identifies a default assembly loss rate for factory built equipment under the broad category of "other stationary refrigeration and air conditioning equipment" of 2-3%. Based on this information, ICF maintains the previous assumption of 2% in 2010 and beyond, and a slightly higher loss rate in earlier years (i.e., 3% from 1990-2000, which is assumed to decline linearly to reach 2% by 2010).

Operational Loss Rate

One UK industry representative estimates that condensing units today leak at roughly 10-12% per year, representing an improvement over earlier years (HARP 2011). IPCC (1996) does not specifically identify an annual leak rate for condensing units but identifies the operational leak rate for the broad category of "other stationary refrigeration and air conditioning equipment" as 3-17%. IPCC (2006) identifies a default value of 10-35% for medium and large commercial refrigeration while IPCC (2000) identifies a default leak rate value of 10-30%. RTOC (2010) and Oko-Recherche et al. (2011) both estimate refrigerant losses to range from at least 7-12%. Oko-Recherche et al. (2011) project that leakage rates of condensing units may decrease to as low as 6% by 2050.

Based on this information, ICF assumes a lifetime leak rate of 10% in 2010 with a reduction to 7% by 2030, as technician maintenance practices and equipment leak tightness is assumed to improve over time. ICF maintains a higher loss rate for earlier years (i.e., 30% in 1990, 20% in 2000) based on the assumption that leak rates have improved over time.

Disposal Loss Rate

EC (2010) assumes that small commercial refrigeration equipment typically has 70% of charge remaining at disposal with 95% of that charge being technically recoverable; this implies a loss rate of 4% or greater, depending on recovery compliance levels. Assumptions provided by IPCC (2006) imply that at least 15-30% of the initial charge is lost at disposal (i.e., assuming 50-100% of the charge remains at EOL and a recovery efficiency of up to 70%), while Oko-Recherche et al. (2011) assume a disposal loss rate 50%. IPCC (1996) implies a disposal loss rate of 18% or greater, based on the assumption that 90% of the charge remains at disposal for the broad category of "other stationary refrigeration and air conditioning equipment" with up to 80% recovered. IPCC (2000) estimates that 80-90% of the charge remaining at EOL is recoverable. This information is summarised in the table below.

Table 32. Summary of Available Disposal Loss Estimates for Condensing Units

Source	Percent of Original Charge Remaining at EOL	Recovery Efficiency (% of remaining charge that can be recovered)	Estimated Disposal Loss (as % of original charge)
Oko-Recherche et al. (2011)	NA	NA	50%
EC (2010)	70%	95%	≥4%
IPCC (1996)	90%	80%	≥18%
IPCC (2000)	NA	80-90%	≤10-20%
IPCC (2006)	50-100%	70%	≥15-30%

Based on this information, ICF increased the previous disposal loss rate from 5% to 15% in 2010. The higher rate accounts for losses likely to occur during the recovery process itself, as well as potential non-compliance with refrigerant recovery requirements. The 15% estimate is above the minimum disposal loss rates estimated by EC (2010) and within the likely range specified by IPCC (2006), IPCC (2000), and IPCC (1996); it is lower than that estimated for the EU-27 by Oko-Recherche et al. (2011), which is believed to be appropriate as compliance with recovery requirements in the UK is likely higher than the average compliance rate across the entire EU. Furthermore, UK industry experts have indicated that disposal loss rates are not as high as some literature indicate (Marks and Spencer 2011; Gluckman 2011). However, a higher disposal loss rate for earlier years is assumed (i.e., 60% in 1990 and 45% in 2000) as recovery practices and technologies are believed to have improved over time in response to new refrigerant recovery regulations. While these rates are higher than those provided by the IPCC (2000 and 2006), such rates speak to what is technically recoverable, without considering actual recovery practices/compliance rates in-country—which are believed to be lower in the past than today. For future years, ICF assumes a declining rate that reaches 10% by 2030, to account for improvements in recovery compliance and technician practices, as well as recovery technology. All loss rates are assumed to decrease linearly.

Summary

The table below summarises the revised assumptions related to HFC charge size and loss rates.

Table 33. Summary of Revised Charge Size and Loss Rate Assumptions for Condensing Units*

Input	1990	2000	2010	2020	2030-2050
Average HFC Charge Size (kg)	5	5	5	5	5
Manufacturing Loss Rate	3%	3%	2%	2%	2%
Operational Leak Rate	30%	20%	10%	10%	7%
Disposal Loss Rate	60%	45%	15%	15%	10%

*A linear change between identified years is assumed.

4.3.4 Summary of Model Updates

The table below summarises the model updates described above for an indicative list of parameters, based on the research conducted.

Table 34. Comparison of Previous vs. Revised Assumptions for Key Parameters

Input	Previous	Revised
Average HFC charge size (kg) for equipment built in 2010	NA	5
Manufacturing Loss Rate (2010)	2%	2%
Operational Leak Rate (2010)	3%	10%
Disposal Loss Rate (2010)	5%	15%
Lifetime (years)	14	14

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4.4 Centralised Supermarket Refrigeration Systems

4.4.1 Overview of Previous Model Assumptions

The supermarket systems end-use previously used a top down approach to model HFC consumption and emissions. HFCs were assumed to first enter the market in 1993, growing to a total installed base of 6,125 MT in 2010. Assumptions for the penetration of HFCs entering the market in new or retrofit equipment are summarized below in Table 35.

Table 35. Previous Market Penetrations of HFC Refrigerants into New/Retrofitted Units

	134a	404A	407C	410A	417A*	422D*	407A	422A*	507
1990	25%	50%	15%	5%	-	-	-	-	5%
2003	10%	88%	-	-	1%	-	1%	-	-
2007	8%	84%	-	-	1%	4%	1%	2%	-
2008 - 2050	2%	96%	-	-	-	-	2%	-	-

* R-417A, R-422A, and R-422D are used to convert HCFC-22 equipment.

In the previous model, equipment was assumed to have a lifetime of 8 years. Previous HFC refrigerant loss rate assumptions for select years are summarized in Table 36 below.

Table 36. Previous HFC Refrigerant Loss Rate Assumptions

Input	1990	2000	2010	2050
Manufacturing Loss Rate	3%	2%	2%	2%
Lifetime Leak Rate	30%	20%	11%	3%
Disposal Loss Rate	10%	8%	5%	4%

4.4.2 End-Use Definition

Refrigeration systems that are comprised of racks of compressors installed in a machinery room. These systems are commonly used in supermarket applications.

4.4.3 Summary of Research Findings and Updates

Equipment Stocks and Growth Rate

Stock Data

ICF used the store area of supermarkets in the UK as a proxy to estimate the amount of refrigerant in use across the end-use. According to the Institute of Grocery Distribution, the number of supermarkets in the UK today is estimated at roughly 8,000, representing an area of 109.1 million square feet (IGD 2010), which is equivalent to about 10.1 million square metres. ICF used this statistic in combination with a charge per square metre assumption (i.e., 0.26 kg/m^2 in 2010) to estimate the installed refrigerant charge, which is assumed to total approximately 330 kg per store, or 2.6 million kg sector-wide in 2010.

Market Growth Rates

According to Oko-Recherche et al. (2011), growth rate assumptions are assumed to be 3% for 2010-2020 and 1.5% for 2020-2050. Since 1999, IGD (2010) reports an annual average market performance growth of 4% for the entire grocery retail market (which includes sales from convenience stores and online purchases). Based on this information, ICF assumes a growth rate of 3% for 2010-2020 and 1.5% for 2020-2030 to estimate future stocks; ICF assumes no market growth beyond 2030. For 1990-2009, historic GDP data from the World Bank (2011) is used to back-cast stock estimates, with any negative growth zeroed-out (given that the recent economic downturn is not believed to have impacted the refrigeration sector to the same extent as the consumer goods sectors).

Equipment Lifetime

Equipment lifetime refers to the lifetime of the refrigeration equipment located in the back of the store, not the lifetime of the display cases located on the sales floor. Both EC (2010) and Oko-Recherche et al. (2011) assume an equipment lifetime of 12 years while IPCC (2006) assumes a lifetime of 7-15 years for medium and large commercial refrigeration and IPCC (2000) assumes a lifetime of 7-10 years. RTOC (2010) estimates that in developed countries supermarket equipment is partially or totally renewed every 7 to 10 years. Conversely, Gluckman (2011a) estimates a much higher lifetime for UK supermarket refrigeration systems of 15-20 years. Similarly, Marks and Spencer (2011) estimates a lifetime of nearly 20 years for major capital plants in the UK retail food sector. Based on this information, ICF increased the equipment lifetime to 18 years, giving greater weight to the UK-specific estimates.

Refrigerant Use and Transitions

During the 1990s, HCFC-22, R-502, and CFC-12 were the dominant refrigerants used in supermarket refrigeration systems. HFCs gradually began to penetrate the market in the mid/late 1990s, leading to the complete phase-out of R-502 and CFC-12 in new equipment by 1995 and of HCFC-22 by 2001. R-404A dominates the current market today (at roughly 90%), while R-407A accounts for most of the remainder; R-407A, R-134A, and R-407F also have small shares (HARP 2011).

In the coming years, non-HFC refrigerants are expected to penetrate the market, as well as HFOs (F-GAS 2009, RTOC 2010, EIA 2011, Honeywell 2011). Already, ammonia secondary loops and CO_2/HFC-134a systems are in use in the UK; over the next 20-30 years, a steep rise in the use of ammonia, CO_2, and HFOs is expected (Honeywell 2011). According to Marks and Spenser (2011), CO_2 will be a major player. Gluckman (2011a) generally anticipates the replacement of R-404A with medium GWP HFCs (i.e., HFC-134a, R-407F), HFOs, or natural refrigerants in retail food equipment in the coming years. Both SKM Enviros (2011) and JTL Systems (2011) believe that ammonia will likely play a relatively small role. Mexichem Fluor (2011) maintains that the availability of HFOs and the drive to transition to low-GWPs will influence this transition. According to EIA (2011), a total of 239 stores in the UK were already using climate-friendly refrigeration in 2009, largely CO_2-based technologies. EIA (2011) also reports that nine retailers have announced measures to reduce their use of HFCs; Marks and Spencer, Tesco, Morrisons, Lidl, Co-operative Group, Aldi, Midlands Co-operative, Sainsbury's, and Waitrose; the latter three having made commitments to stop using HFCs in any future projects.

According to Honeywell (2011) a significant number of UK supermarkets have and are continuing to retrofit their HCFC-22 equipment, primarily with R-422D but also with R-417A and R-422A. According to Honeywell (2011), such retrofits began in 2005 and peaked in 2010, although another spike in retrofit activity is projected for 2014. According to industry sources, major supermarket chains have also begun retrofitting R-404A equipment with R-407F and R-407A starting a few years ago (Honeywell 2011, Mexichem Fluor 2011). However, other industry sources maintain that retrofit activity has not yet been significant, and has involved only R-422D and some R-407A (HARP 2011). R-407F can also be used in new stores and is expected to be used more widely in the near-term, due to its lower GWP relative to R-404A, as well as its high efficiency (Honeywell 2011). However, according to Marks and Spencer (2011), retrofits will play only a small part in systems, as replacement will be the main direction to avoid duplication of spending.

Based on this information, the tables below summarise the revised market penetrations of refrigerants into new and retrofitted centralised refrigeration systems for key years. The percentages in the latter table represent the portion of original refrigerant remaining in eligible equipment (i.e., equipment with 25-75% of its useful life remaining) that is replaced by a retrofit refrigerant.

Table 37. Revised Market Penetration of Refrigerants into New Centralised Systems*

Year	12	502	22	134a	404A	407A	407C	407F	HFOs	HCs	744	717
1990 - 1993	40%	40%	20%	-	-	-	-	-	-	-	-	-
1995	-	-	95%	1%	3%	-	1%	-	-	-	-	-
1998	-	-	30%	4%	62%	-	4%	-	-	-	-	-
2001	-	-	-	8%	84%	-	8%	-	-	-	-	-
2007	-	-	-	6%	85%	-	8%	-	-	-	1%	-
2010	-	-	-	6%	80%	6%	-	-	-	2%	5%	1%
2015	-	-	-	12%	8%	20%	-	26%	6%	7%	15%	6%

Year	12	502	22	134a	404A	407A	407C	407F	HFOs	HCs	744	717
2020	-	-	-	-	-	-	-	15%	20%	15%	40%	10%
2030	-	-	-	-	-	-	-	-	30%	20%	40%	10%
2050	-	-	-	-	-	-	-	-	30%	20%	40%	10%

* For years not listed, a linear change in market penetration between identified years is assumed.

Table 38. Revised Market Penetrations of Retrofit Refrigerants into Existing Eligible Equipment*

Original	Retrofit	1990–1999	2000	2001	2005	2009	2010	2012	2014	2015	2020	2030-2050
12	22	-	100%	-	-	-	-	-	-	-	-	-
502	22	-	100%	-	-	-	-	-	-	-	-	-
22	417A/422D**	-	-	-	-	2%	70%	2%	50%	10%	-	-
404A	407A/407F**	-	-	-	-	-	1%	2%	3%	3%	2%	-

* Eligible equipment for this end-use is defined as equipment with 25-75% of its useful life remaining. Figures were developed based on confidential business information supplied by Honeywell (2011) and are expressed as a percent of total metric tonnes of the remaining original refrigerant installed in existing eligible equipment. A linear change between identified years is assumed.

** For modelling purposes, the GWP of R-422D and R-407F are used for retrofits of HCFC-22 and R-404A equipment, respectively.

HFC Charge Size and Loss Rates

Charge Size

Charge sizes for supermarket equipment can vary significantly depending on their size. IPCC (2006) and IPCC (2000) estimate that large and medium commercial refrigeration systems can have charges ranging from 50-2,000 kg, while IPCC (1996) estimates a charge size of 10-230 kg for all types of retail food refrigeration equipment. TEAP (2009) estimates that large supermarket refrigeration systems have charges that vary from 300-3,000 kg, while RTOC (2010) estimates a range of 100-3,000 kg. Oko-Recherche et al. (2011) assume that the average charge size of centralised systems in the EU is 230 kg. EC (2006) and EC (2010) estimate that on average supermarket systems in the EU have a charge of 300 kg. This information is summarized in the table below.

Table 39. Summary of Charge Size Estimates for Centralised Systems

Source	Charge Size Estimate (kg)[a]
EC (2006)	300
EC (2010)	300
IPCC (2006)	50 – 2,000[b]
IPCC (2000)	50 – 2,000[ab]
IPCC (1996)	10 – 230[b]
Oko-Recherche et al. (2011)	230
RTOC (2010)	100 – 3,000
TEAP (2009)	300 – 3,000

[a] Estimates are not shown in kg/m^3 because assumed average store sizes are not provided in all sources.
[b] Estimate not specific to centralised systems.

Since store size (rather than number of systems) will be used as a proxy to estimate refrigerant use, a ratio of refrigerant per store area will be used as an input in the model rather than average charge size. Oko-Recherche et al. (2011) estimate that in France and Germany, supermarkets contain 0.230 – 0.287 kg/m^2. Based on this information, ICF assumes that each supermarket square metre in the UK uses 0.26 kg of refrigerant in 2010, with a slightly higher ratio (0.28 and 0.27 kg/m^2) in 1990 and 2000, and a slightly lower ratio (0.25 and 0.23 kg/m^2) in 2020 and 2030. The assumed reduction in average charge over time is due to changes in system design which are being prompted by a push to minimise charge sizes and resulting leakage. The 2010 assumption implies an average supermarket charge size of almost 330 kg (assuming 8,000 supermarkets in the UK totalling 10.1 million m^2 [IGD 2010]). This estimate is above the average charge estimated for the EU by Oko-Recherche et al. (2011) but well within the wide range provided by RTOC (2010), TEAP (2009), and IPCC (1996, 2000, 2006).

Manufacturing Loss Rate

IPCC (2006) and IPCC (2000) estimate that initial emissions from medium and large commercial refrigeration are between 0.5% and 3%. IPCC (1996) does not specifically identify a manufacturing loss rate for centralised supermarket systems but identifies a default assembly loss rate for site built equipment under the broad category of "other stationary refrigeration and air conditioning equipment" of 4-5%. SKM Enviros (2011) estimates that manufacturing loss rates average about 2%. Accordingly, ICF maintains the manufacturing loss rate of 2%.

Operational Loss Rate

RTOC (2010) assumes a typical small supermarket has a leak rate of 15-25% while a large supermarket has a leak rate of 20-35%. IPCC (1996) does not specifically identify an annual leak rate for centralised supermarket systems but identifies an operational leak rate for the broad category of "other stationary refrigeration and air conditioning equipment" of 3-17%. IPCC (2006) identifies a default value of 10-35% for medium and large commercial refrigeration while IPCC (2000) assumes a default value of 10-30%. Oko-Recherche et al. (2011) assume a lifetime leak rate of 15% and projects that leakage rates will decrease to 9.6% under the F-gas Regulation by 2015. EPEE (2011) assumes an average leak rate of 22% across the EU-27. A survey conducted by EIA (2009) found that the lowest reported leak rate from UK supermarkets using centralised systems was about 14%.

Based on this information, ICF increased the lifetime leak rate from 11% to 18% in 2010 but decreased it to 15% starting in 2015, 10% in 2020 and 7% starting in 2030—as technician maintenance practices and equipment leak tightness is assumed to improve over time. ICF assumes a higher loss rate in 1990, of 30%, consistent with the previous model. The 2010 leak rate of 18% is lower than the EPEE (2011) leak rate of 22% given that average UK leak rates are believed to be lower than those across the whole EU-27; however, this rate is higher than the Oko-Recherche (2011) estimate of 15%, which ICF believes to be overly optimistic. These annual average leak rate estimates were supported by a major UK retailer, Marks and Spencer (2011).

Disposal Loss Rate

At end-of-life, a 30% loss rate is assumed by Oko-Recherche et al. (2011). EC (2010) assumes that large commercial refrigeration equipment have 70% of charge remaining at disposal with 95% of that charge technically recoverable; this implies a loss rate of 4% or greater, depending on recovery compliance levels. Assumptions provided by IPCC (2006) indicate 15-30% or more of the initial charge is lost at disposal (i.e., assuming 50-100% of the charge remains at disposal with a recovery efficiency of up to 70%). IPCC (2000) estimates that 80-90% of the charge remaining at EOL is recoverable. IPCC (1996) implies a disposal loss of 18%, assuming 90% of the charge remains at disposal for the broad category of "other stationary refrigeration and air conditioning equipment," while 80% is recovered if recovery practices are used. One UK industry expert anticipates high regulatory compliance and estimates a disposal loss rate of only 5-10% (Gluckman 2011b). Additionally, major UK retailer Marks and Spencer (2011) maintains that disposal losses in the large retail food refrigeration sector is lower than 10%. This information is summarised below.

Table 40. Summary of Available Disposal Loss Estimates for Centralised Systems

Source	Percent of Original Charge Remaining at EOL	Recovery Efficiency (% of remaining charge that can be recovered)	Estimated Disposal Loss (as % of original charge)
EC (2010)	70%	95%	≥4%
Gluckman (2011b)	NA	NA	5-10%
IPCC (1996)	90%	80%	≥18%
IPCC (2000)	NA	80-90%	≤10-20%
IPCC (2006)	50-100%	70%	≥15-30%
Marks and Spencer (2011)	NA	NA	≤10%
Oko-Recherche et al. (2011)	NA	NA	30%

Based on the input from UK industry, ICF assumes a disposal loss rate of 8% in 2010, declining linearly to reach 5% in 2030. The rate accounts for likely losses that occur during the recovery process, as well as potential non-compliance with refrigerant recovery requirements. The lower loss rate in 2030 is assumed in response to refrigerant recovery regulations as well as the assumption that recovery practices and technologies have improved over time. Similarly, ICF assumes a higher loss rate in earlier years—50% in 1990, declining linearly to 30% in 2000.

Summary

The table below summarises the revised assumptions related to HFC charge size and loss rates.

Table 41. Summary of Revised Charge Size and Loss Rate Assumptions for Centralised Systems*

Input	1990	2000	2010	2020	2030-2050
Average HFC Charge Size (kg/m^2)	0.28	0.27	0.26[a]	0.25	0.23
Manufacturing Loss Rate	2%	2%	2%	2%	2%
Operational Leak Rate	30%	30%	18%	10%	7%
Disposal Loss Rate	50%	30%	8%	8%	5%

* For years not listed, a linear change between identified years is assumed.
[a] This implies an approximate average charge size of 330 kg per store.

4.4.4 Summary of Model Updates

The table below summarises the model updates described above for an indicative list of parameters, based on the research conducted.

Table 42. Comparison of Previous vs. Revised Assumptions for Key Parameters

Input	Previous	Revised
Average HFC charge size (kg/m^2)) for equipment built in 2010	NA	0.26
Manufacturing Loss Rate (2010)	2%	2%
Operational Leak Rate (2010)	11%	18%
Disposal Loss Rate (2010)	5%	8%
Lifetime (years)	8	18

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4.5 Industrial Systems

4.5.1 Overview of Previous Model Assumptions

The industrial systems end-use previously used a top-down approach to model HFC consumption and emissions. HFCs were assumed to first enter the market in 1993, growing to a total installed base of 5,256 MT in 2010. Assumptions for the penetration of HFCs entering the market (i.e., installed in newly sold or existing HCFC equipment in a given year) are summarized below.

Table 43. Previous Market Penetrations of Refrigerants into New/Retrofitted Units

	134a	404A	407C	410A	507	417A*	422D*	422A*
1990	35%	20%	25%	10%	10%	-	-	-
2003	25%	60%	4%	-	10%	1%	-	-
2007	20%	55%	2%	1%	15%	3%	3%	1%
2008 - 2050	10%	58%	-	1%	30%	-	1%	-

* R-417A, R-422A, and R-422D are used to convert R-22 equipment.

In the previous model, equipment was assumed to have a lifetime of 16 years. Previous leak rate assumptions for select years are summarized in the table below.

Table 44. Previous Refrigerant Loss Rate Assumptions

Input	1990	2000	2010	2050
Manufacturing Loss Rate	3%	2%	1%	-
Lifetime Leak Rate	20%	12%	8%	5%
Disposal Loss Rate	10%	8%	5%	4%

4.5.2 End-Use Definition

Refrigeration systems including industrial process refrigeration and cold storage.

4.5.3 Summary of Research Findings and Updates

Equipment Stocks and Growth Rate

Stock Data

A draft UK survey of 132 food manufacturing and cold storage sites found a total of 2,278 industrial refrigeration systems in operation at these facilities alone – that is an average of 17 systems at each site (SKM Enviros 2011b). By extrapolating this number to the estimated 1,000+ industrial facilities believed to operate in the UK across all relevant sectors (e.g., food factories, cold stores, petrochemicals, pharmaceuticals, printing, and plastics) (Gluckman 2011), ICF estimates that roughly 20,000 individual industrial refrigeration systems are currently in operation in the UK. Based on Oko-Recherche (2011), it is assumed that the food manufacturing and cold storage industry represents approximately 75% of industrial refrigeration facilities, with the remaining 25% being in the chemical and pharmaceutical industries.

Market Growth Rates

Because industrial systems are used in many different types of industries, including chemical, food, beverage, and pharmaceutical with different growth projections, no single industry growth rate for the UK that was identified as an appropriate proxy for projecting growth in this end-use. EC (2010) estimates the 2010-2020 market growth rates for industrial systems to be 2% annually, and 1% annually from 2020-2050. Oko-Recherche et al. (2011) estimate a 4% growth rate from 2010-2020 and 3% from 2020-2030. According to some industry experts, significant growth of industrial systems in the UK is not expected in future; modest growth on the order of 1-2% per year can be expected in the near-term (Honeywell 2011a, STAR Refrigeration 2011, Gluckman 2011). Based on this information, ICF assumes a growth rate of 2% from 2010 to 2020, 1% from 2020 to 2030, and 0% from 2030 onward. For 1990-2009, historic GDP data from the World Bank (2011) is used to back-cast stock estimates, with any negative growth zeroed-out (given that the recent economic downturn is not believed to have impacted the industrial refrigeration sector to the same extent as the consumer goods sectors).

Equipment Lifetime

IPCC (2006) assumes a default lifetime of 15-30 years for industrial systems, while IPCC (2000) assumes a default lifetime of 10-20 years. EC (2010) assumes a lifetime of 20 years and Oko-Recherche et al. (2011) assumes 30 years. Based on this information, ICF increased the previous lifetime assumption from 16 to 25 years. This is outside of the IPCC (2000) range but is the central estimate from the two EU-based studies, and is also within the IPCC (2006) range.

Refrigerant Use and Transitions

EC (2006) estimates that in many European countries, ammonia (R-717) is used in up to 80% of all systems. EIA (2009) states that ammonia is the most energy and cost-efficient refrigerant available, but toxicity concerns limit its use in industrial systems used in store fronts. According to EIA (2009), three major UK retailers currently use 100% ammonia in their distribution centres, while others use a combination of ammonia and HFCs or only HCFCs and HFCs. One UK industry expert estimates that only 20-30% of new industrial systems installed today use HFCs; the vast majority use ammonia, with some HCs, and minimal use of CO_2 (HARP 2011). Across the EU, Oko-Recherche et al. (2011) estimate that ammonia and other natural refrigerants account for 55% of new sales of industrial systems, while R-404A accounts for the remaining 45%. Oko-Recherche et al. (2011) project that this refrigerant balance will remain constant through 2030.

A draft UK survey of 132 food and drink manufacturing and cold storage sites found that of the 2,278 individual refrigeration systems found in these facilities, 35% of systems still use HCFC-22. R-404A is the most popular of the HFCs and represents 48% of the quantity of HFCs in use. Other relatively common HFCs in use include R-407C and R-410A. Ammonia only represents 6% of the number of systems, but is dominant in terms of refrigerant quantity – accounting for 56% of the total of all refrigerants in the survey (SKM Enviros 2011b)

According to HARP (2011), there are still many hundreds of tons—if not thousands of tons—of HCFC-22 installed in industrial systems in the UK; most facilities are waiting as long as possible to replace these systems (i.e., until the end of 2014), with only a minimal number of retrofits to R-422D having occurred to date. Conversely, according to Honeywell (2011a), a significant number of HCFC-22 industrial systems in the UK were retrofitted to HFC blends, primarily R-422D but also R-417A. Honeywell maintains that limited retrofit activity began in 2005 and peaked in 2010, although another spike is projected in 2014 prior to the complete phaseout of HCFC-22 in the EU. Honeywell (2011b) also indicates that R-407A and R-407F are being used today to retrofit existing R-404A equipment.

It is anticipated that the use of high-GWP HFCs will gradually be replaced over time, likely being fully replaced in new equipment by 2030, as low-GWP HFOs become available in this application (Honeywell 2011, STAR Refrigeration 2011). The Food and Drink Federation (2011) similarly projects HFOs will play a significant role in the future market as HFCs are replaced, and that HCs and CO2 will be used in some applications where cost, health, and safety concerns can be adequately addressed.

Based on this information, ICF assumes the market penetrations of refrigerants in new and retrofitted units sold in the UK as shown in the tables below. The percentages in the latter table represent the portion of original refrigerant remaining in eligible equipment (i.e., equipment with 20-70% of its useful life remaining) that is replaced by a retrofit refrigerant.

Table 45. Revised Market Penetration of Refrigerants into New Industrial Systems*

Year	12	502	22	134a	404A	407C	410A	507	HFOs	HCs	744	717
1990	15%	15%	30%	-	-	-	-	-	-	-	-	40%
1993	-	-	55%	3%	1%	-	-	1%	-	-	-	40%
2000	-	-	40%	5%	14%	-	-	1%	-	-	-	40%
2001	-	-	-	5%	48%	-	-	2%	-		-	45%
2007	-	-	-	5%	35%	8%	2%	2%	-	2%	1%	45%
2010	-	-	-	2%	30%	8%	3%	2%	-	3%	2%	50%

Year	12	502	22	134a	404A	407C	410A	507	HFOs	HCs	744	717
2015	-		-	-	12%	2%	-	-	6%	5%	5%	70%
2020	-		-	-	10%	-	-	-	10%	5%	5%	70%
2030-2050	-		-	-	-	-	-	-	17%	8%	5%	70%

* For years not listed, a linear change in market penetration between identified years is assumed.

Table 46. Revised Market Penetrations of Retrofit Refrigerants into Existing Eligible Equipment*

Original	Retrofit	1990–1999	2000	2001	2005	2009	2010	2012	2014	2015	2020	2030-2050
12	22	-	100%	-	-	-	-	-	-	-	-	-
502	22	-	100%	-	-	-	-	-	-	-	-	-
22	417A/422D**	-	-	-	-	10%	35%	10%	20%	100%	-	-
404A	407A/407F**	-	-	-	-	1%	1%	2%	3%	3%	2%	-

* Eligible equipment for this end-use is defined as equipment with 20-70% of its useful life remaining. Figures were developed based on confidential business information supplied by Honeywell (2011) and are expressed as a percent of total metric tonnes of the remaining original refrigerant installed in existing eligible equipment. A linear change between identified years is assumed.
** For modelling purposes, the GWP of R-422D and R-407F are used for retrofits of HCFC-22 and R-404A equipment, respectively.

HFC Charge Size and Loss Rates

Charge Size

Based on the draft survey results prepared by Defra (2011), HCFC-22 systems used in the food manufacturing and cold storage sectors have an average charge of 95 kg, while HFC-134a and R-404A systems have an average charge of 64 kg and 76 kg, respectively. Other HFC based systems range in charge from 20-46 kg.[9] Similarly, the Food and Drink Federation (2011) indicates that a charge size of 20-80 kg is typical in food and drink manufacturing equipment. Assuming 17 systems per facility (based on preliminary data from Defra [2011]), the Defra charge range for HFCs translates to an average charge of 340-782 kg per industrial facility, whereas the Food and Drink Federation estimate translates to 340-1,360 kg.

EC (2010) assumes a total charge size of 850 kg for HFCs and 1,000 kg for HCFCs in industrial systems. IPCC (2006) and IPCC (2000) assume a range of 10-10,000 kg for industrial systems, while IPCC (1996) assumes a range of 340-9,100 kg. Oko-Recherche et al. (2011) assume a total charge size of 650 kg for small industrial systems and 4,000 kg for large industrial systems. It is unclear how each report defines an industrial "system", so it difficult to directly compare these estimates to those provided in Defra (2011) or by the Food and Drink Federation (2011).

Table 47. Summary of Charge Size Estimates for Industrial Systems

Source	Charge Size Estimate (kg)
Defra (2011)	95 (HCFC-22) 64 (HFC-134a) 76 (R-404A) 20-46 (Other HFCs)
EC (2010)	1,000 (HCFCs) 850 (HFCs)
IPCC (2006)	10 – 10,000
IPCC (2000)	10 – 10,000
IPCC (1996)	340 – 9,100
Oko-Recherche et al. (2011)	650 – 4,000

Based on this information, ICF assumes an average HFC charge size of 65 kg for 2010 onwards and 95 kg for historical years. Assuming 17 systems per facility based on preliminary data from Defra (2011), this would translate to an average charge of 1,105-1,615 kg per industrial facility. These charge sizes are based most heavily on the UK-specific estimates from the Defra survey and the Food and Drink Federation; they are also within the IPCC default ranges.

[9] This implies an average of approximately 350-1,500 kg of HFC refrigerant charge per industrial facility, assuming 17 systems per facility.

Manufacturing Loss Rate

IPCC (2006) and IPCC (2000) estimate the manufacturing loss rate for industrial refrigeration to be between 0.5% and 3%. IPCC (1996) does not specifically identify a manufacturing loss rate for industrial refrigeration systems but identifies a default assembly loss rate for site built equipment under the broad category of "other stationary refrigeration and air conditioning equipment" of 4-5%. SKM Enviros (2011a) indicated that a loss rate of 4% for this end-use seemed high. Accordingly, ICF maintained the manufacturing loss rate of 1%.

Operational Loss Rate

The IPCC (2006) and IPCC (2000) default leak rate for industrial systems is between 7% and 25%. IPCC (1996) does not specifically identify an annual leak rate for industrial refrigeration systems but identifies an operational leak rate for the broad category of "other stationary refrigeration and air conditioning equipment" of 3-17%. Oko-Recherche et al. (2011) estimate a leak rate of 8%.

Based on this information, ICF maintained the lifetime leak rate of 8% in 2010 but assumes it will decrease in future to reach 7% by 2030, as technician maintenance practices and equipment leak tightness improves over time. ICF also assumes a leak rate of 15% in 1990 and 2000 (with a linear decrease from 2000 to 2010 levels), to similarly account for technological improvements over time.

Disposal Loss Rate

One UK industry expert indicated that more than 90% of the original charge for industrial equipment typically remains at EOL and that recovery is done very effectively, since refrigerant is recovered on-site for large systems at EOL (Gluckman 2011). Oko-Recherche et al. (2011) assume a disposal loss rate for industrial refrigeration systems is 30%. EC (2010) estimates that 60% of refrigerant remains at EOL, of which 81% is technically recoverable; this implies a disposal loss emissions of 11% or greater, depending on compliance with recovery requirements. Assumptions provided by IPCC (2006) indicate 5-10% of the initial charge is loss during disposal (i.e., assuming 50-100% of the charge remains at EOL and a recovery efficiency of up to 90%). IPCC (2000) estimates that 80-90% of the charge remaining at EOL is recoverable. IPCC (1996) estimates that 90% of the charge remains at disposal for the broad category of other stationary refrigeration and air conditioning equipment while 80% is recovered if recovery practices are used; thus implying a disposal loss rate of 18%. This information is summarised in the table below.

Table 48. Summary of Available Disposal Loss Estimates for Industrial Systems

Source	Percent of Original Charge Remaining at EOL	Recovery Efficiency (% of remaining charge that can be recovered)	Estimated Disposal Loss (as % of original charge)
EC (2010)	60%	81%	≥11%
Gluckman (2011)	>90%	NA	≤10%
IPCC (1996)	90%	80%	≥18%
IPCC (2000)	NA	80-90%	≤10-20%
IPCC (2006)	50-100%	90%	≥5-10%
Oko-Recherche et al. (2011)	NA	NA	30%

Based on this information, ICF increased the disposal loss rate of 5% to 15% today, 50% in 1990, and 30% in 2000 (with rates assumed to decline linearly during interim years). ICF decreased the loss rate further over time, reaching 10% by 2020, in light of assumed improvements in recovery technologies and technician practices/knowledge. ICF is not increasing the 2010 loss rate to the same level estimated by Oko-Recherche et al. (2011) in light of higher expected compliance with refrigerant recovery provisions in the UK versus the average EU-27 (based on UK industry input).

Summary

The table below summarises the revised assumptions related to HFC charge size and loss rates.

Table 49. Summary of Charge Size and Loss Rate Assumptions for Industrial Systems*

Input	1990	2000	2010	2020	2030-2050
Average HFC Charge Size (kg)	95	95	65**	65	65
Manufacturing Loss Rate	1%	1%	1%	1%	1%
Operational Leak Rate	15%	15%	8%	8%	7%
Disposal Loss Rate	50%	30%	15%	10%	5%

*For years not listed, a linear change between identified years is assumed.
**This implies an approximate average charge size of 1,105 kg per facility.

4.5.4 Summary of Model Updates

The table below summarises the model updates described above for an indicative list of parameters, based on the research conducted.

Table 50. Comparison of Previous vs. Revised Assumptions for Key Parameters

Input	Previous	Revised
Average HFC charge size (kg) for equipment built in 2010	NA	65
Manufacturing Loss Rate (2010)	1%	1%
Operational Leak Rate (2010)	8%	8%
Disposal Loss Rate (2010)	5%	15%
Lifetime (years)	16	25

4.5.5 References

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4.6 Small Stationary Air Conditioning

4.6.1 Overview of Previous Model Assumptions

The small stationary air conditioning end-use previously used a top-down approach to model HFC consumption and emissions. HFCs were assumed to first enter the market in 1995, growing to a total installed base of 5,912 MT in 2010. Assumptions for the penetration of HFCs entering the market (i.e., installed in newly sold or existing HCFC equipment in a given year) are summarized below.

Table 51. Previous Market Penetrations of HFC Refrigerants into New/Retrofitted Units

	134a	404A	407C	410A	417A*	422D*
1990	25%	-	40%	35%	-	-
2003	10%	3%	70%	15%	2%	-
2007	10%	3%	51%	31%	4%	1%
2008 - 2050	5%	1%	51%	43%	-	-

* R417A and R422D are used to convert R22 equipment

In the previous model, equipment is assumed to have a lifetime of 13 years. Previous leak rate assumptions for select years are summarized in the table below.

Table 52. Previous HFC Refrigerant Loss Rate Assumptions

Input	1990	2000	2010	2050
Manufacturing Loss Rate	3%	2%	2%	2%
Lifetime Leak Rate	30%	12%	8%	5%
Disposal Loss Rate	10%	8%	5%	4%

4.6.2 End-Use Definition

Includes small self-contained AC units (including window units) and non-ducted split AC systems. Units are used primarily in commercial applications, but there is some use in the residential sector. System cooling capacities typically range from 3 to 12 kW

4.6.3 Summary of Research Findings and Updates

Equipment Stocks and Growth Rate

Stock Data

ECODESIGN Lot 10 Draft (2008) presented total UK stocks and sales for small stationary AC systems—i.e., moveables, reversible split, and cooling only split systems with capacities of 12 kW or less—from 2005 through 2030. According to this source, the total stock of small stationary AC systems in the UK was estimated at approximately 4.6 million in 2010. ICF used this dataset for estimating UK stocks. Based on anecdotal information (Gluckman 2011), it is assumed that 90% of units are manufactured pre-charged outside of the UK.

Market Growth Rates

BSRIA (2011) provides annual UK sales for various types of small AC equipment from 2009 to 2014 and estimates the annual change in sales for each of these equipment types. Specifically, annual change between 2009-2014 is estimated to be 2.5% for window and portable units and 5.9% for split systems; based on a weighted average of these units, average annual growth is 2.5%.

ECODESIGN Lot 10 Draft (2008) provides annual UK sales and stock estimates and projections for small AC equipment from 2005 to 2030. From 2015-2020, the annual change is 4%, from 2020-2025, annual growth is estimated to be 2%, and from 2025-2030, annual growth is estimated to be 1%.

Based on ECODESIGN Lot 10 Draft (2008) and BSRIA (2011), ICF assumes a growth rate of 6% from 2010-2015, 4% from 2015-2020, 2% from 2020-2025, 1% from 2025-2030, and 0% from 2030 onward.The average annual growth rate of stock data from 2005-2010 from ECODESIGN Lot 10 Draft (2008) is used to back-cast stock estimates for 1990-2004.

Equipment Lifetime

Both EC (2010) and Oko-Recherche et al. (2011) estimate a lifetime of 10 years for small stationary AC units, while IPCC (2006) assumes the lifetime is between 10 and 20 years and IPCC (2000) assumes a lifetime of 10-15 for all residential and commercial AC. According to EPEE (2011), average lifetime is 10 to 15 years. Based on this information, ICF maintains the equipment lifetime of 13 years.

Refrigerant Use and Transitions

CFC-12 was phased out of new stationary AC equipment by 1995, which is when HFCs entered the refrigerant market. Oko-Recherche et al. (2011) assume the market is comprised 100% of HFCs in 2010 and projects that by 2020, 3% of the market will use alternatives, reaching 5% by 2050. Honeywell (2011) projects low-GWP HFOs to begin displacing HFC-410A in 2015. SKM Enviros (2011) predicts HFO blend use in small stationary AC systems, but not until at least 2015, when HFOs are likely to become available outside of the motor vehicle air conditioning market.

Currently, there are very few viable low-GWP options to replace HFC refrigerants in small stationary AC, although manufacture of HC units has begun in China and elsewhere (GREE 2010). HFC-32 has been investigated for use as a replacement for HCFC-22 in China, Indonesia, and Japan, so could make its way to the UK market in future. R-290 may also be used in these and other small types of equipment (EPA 2010). In addition, per EC Directives (such as the Draft Energy Efficiency Directive COM 2011/370), there is a strong push for enhanced energy efficiency in stationary AC units, which will be difficult to meet with low-GWP refrigerants currently available—especially given current standards (i.e., Standard EN 378), which limit the quantity of flammable refrigerants that can be used (Honeywell 2011). For this reason, R-410A is likely to continue dominating the market in the near future, eventually transitioning to HFO blends and HFC-32 as they become more readily available on the market. Hydrocarbons are also projected to penetrate a small portion of the market (for smaller systems) in future.

Based on this information, ICF assumes the market penetrations of refrigerants in new small stationary AC units sold in the UK as shown in the table below.

Table 53. Revised Market Penetration of Refrigerants into New Small Stationary AC*

Year	12	22	134a	404A	407C	410A	32	HFO blends	HCs
1990	60%	40%	-	-	-	-	-	-	-
1995	-	90%	1%	1%	7%	1%	-	-	-
2001	-	-	3%	12%	70%	15%	-	-	-
2010	-	-	-	-	10%	90%	-	-	-
2015	-	-	-	-	-	96%	-	2%	2%
2020	-	-	-	-	-	78%	2%	15%	5%
2030	-	-	-	-	-	45%	5%	45%	5%
2050	-	-	-	-	-	25%	25%	45%	5%

* For years not listed, a linear change in market penetration between identified years is assumed.

HFC Charge Size and Loss Rates

Charge Size

For small AC equipment, EC (2010) assumes a charge size of 2 to 3.5 kg in the EU; EPEE (2010) estimates a charge size for small stationary AC equipment to be between 0.5 and 1.2 kg in the EU; RTOC (2010) assumes the charge size range is between 0.3 and 18 kg for small self-contained ACs small non-ducted single-split, and small ducted split AC systems globally. Oko-Recherche et al. (2011) estimate 0.75 to 1.5 kg for window/portable and single split systems in the EU. IPCC (1996) estimates a global average charge size range of 2-3 kg for residential air conditioning, while the IPCC (2006) and IPCC (2000) default charge size for all residential and commercial AC is 0.5-100 kg. This information is summarized in the table below.

Table 54. Summary of Charge Size Estimates for Small Stationary AC

Source	Charge Size Estimate (kg)
EC (2010)	2 – 3.5
EPEE (2010)	1.5 – 1.2
IPCC (2006)	0.5 – 100[a]
IPCC (2000)	0.5 – 100[a]
IPCC (1996)	2 – 3
Oko-Recherche et al. (2011)	0.75 – 1.5
RTOC (2010)	0.3 – 18

[a] Estimate not specific to small stationary AC units.

Stock data from ECODESIGN Lot 10 Draft (2008) of small stationary AC systems in the UK shows more portable/window units than single-split systems, which typically have lower charge sizes in context of the wide range (0.3 - 100 kg) cited in the sources above. Based on this information, ICF proposes an average charge size of 1.5 kg. This estimate reflects the upper bound of the Oko-Recherche et al. (2011) estimate and is within approximately in the middle of the range provided by the EC (2010)—both of which are specific to the EU. This estimate is also within the IPCC (2006, 2000) and RTOC (2010) global ranges but slightly below the IPCC (1996) default range.

Manufacturing Loss Rate

IPCC (1996) estimates an average assembly loss rate of 2-5% for other stationary refrigeration and AC equipment; while the IPCC (2006) and IPCC (2000) default manufacturing loss rates for residential and commercial AC ranges from 0.2-1%. According to EPEE (2011), manufacturing loss rates for small AC equipment in the EU have considerably reduced in the past years—with one of EPEE's members' factories reporting a 4% loss rate in 2001 and less than a 0.2% loss rate in 2009. Moreover, EPEE maintains that if it is possible to achieve a manufacturing loss rate of 0.2% in some EU countries, it can be assumed that manufacturers in the UK have also achieved this leak rate, or will do so in the coming years, especially in light of production cost impacts. Accordingly, ICF assumes a 0.5% loss rate in 2010, and higher rates historically—i.e., 4% in 1990 and 2% in 2000 (within a linear decline in intervening years)—in line with EPEE's estimates.

Operational Loss Rate

According to EPEE (2011), data from one monitoring system in Hungary indicates a level of emissions between 1%-2% for R-410A systems, while data from the Netherlands shows a level below 0.5%; based on these data, an operation loss rate below 3% can certainly be reached in the UK in the coming years.

Leak rates for the various small stationary AC equipment types range from 5-8% (Oko-Recherche et al. 2011). IPCC (1996) estimates an average annual loss rate of 17% for other stationary refrigeration and AC equipment; while the IPCC (2006) default leak rate assumption is 1-10% and the IPCC (2000) leak rate assumption is 1-5% for all residential and commercial AC.

Based on this information, ICF assumes a loss rate of 3% in 2010—consistent with the EU-specific estimate provided by Oko-Recherche et al.—with a higher loss rate of 5% in 1990 and 2000 (and a linear decrease from 2000 to 2010), to reflect improvements in technology and technician practices over time. By 2020, ICF assumes a loss rate of only 2%, based on information provided by EPEE (2011).

Disposal Loss Rate

Oko-Recherche et al. (2011) estimate a disposal loss rate of 70-30% (depending on AC system classification) while the EC (2010) implies a loss rate of $\geq$8% (based on assumptions that 80% of the charge remains at EOL and 90% of the remaining charge is technically recoverable). According to one industry representative in the UK disposal sector, roughly 1-1.5 kg of refrigerant is typically recoverable from small AC units at disposal—or roughly 50%-75% of the original charge; this implies that at most 25-50% is emitted prior to or during disposal (Overton Recycling 2011). IPCC (1996) implies an average disposal loss rate of 18% for other stationary refrigeration and AC equipment, including transport refrigeration (assuming up to 90% of the original charge remains at equipment EOL and a recovery efficiency of 80%), while IPCC (2006) implies a loss rate of 16% for residential and commercial AC equipment (assuming up to 80% of original charge remains at equipment EOL and a recovery efficiency of 80%). IPCC (2000) assumes that 70-80% of charge remaining at EOL is recoverable. This information is summarised in the table below.

Table 55. Summary of Available Disposal Loss Estimates for Small Stationary AC

Source	Percent of Original Charge Remaining at EOL	Recovery Efficiency (% of remaining charge that can be recovered)	Estimated Disposal Loss (as % of original charge)
EC (2010)	80%	90%	≥8%
IPCC (1996)	90%	80%	≥18%
IPCC (2000)	NA	70-80%	≤20-30%
IPCC (2006)	80%	80%	≥16%
Oko-Recherche et al. (2011)	NA	NA	70-30%
Overton Recycling (2011)	NA	NA	≤50-25%

Based on this information, ICF assumes an average disposal loss rate of 30% in 2010, consistent with the most recent EU estimate provided by Oko-Recherche et al. (2011). In future years, ICF assumes lower loss rates of 25% in 2020 and 20% by 2030 to reflect higher rates of regulatory compliance and improvements in technology/practices over time. Furthermore, ICF assumes higher disposal loss rates—of 65% in 1990 and 40% in 2000—to reflect the same trend. While these loss rates are higher than that provided by IPCC (2000), the IPCC estimate speaks only to what is *technically* recoverable, without considering actual recovery practices/compliance rates in-country—which are believed to be lower in earlier years than today.

Summary

The table below summarises the revised assumptions related to HFC charge size and loss rates.

Table 56. Revised Summary of Charge Size and Loss Rate Assumptions for Small Stationary AC*

Input	1990	2000	2010	2020	2030-2050
Average HFC Charge Size (kg)	1.5	1.5	1.5	1.5	1.5
Manufacturing Loss Rate	4%	2%	0.5%	0.5%	0.5%
Operational Leak Rate	5%	5%	3%	2%	2%
Disposal Loss Rate	65%	40%	30%	25%	20%

* For years not listed, a linear change between identified years is assumed.

4.6.4 Summary of Model Updates

The table below summarises the model updates described above for an indicative list of parameters, based on the research conducted.

Table 57. Comparison of Previous vs. Revised Assumptions for Key Parameters

Input	Previous	Revised
Average HFC charge size (kg) for equipment built in 2010	NA	1.5
Manufacturing Loss Rate (2010)	2%	0.5%
Operational Leak Rate (2010)	8%	3%
Disposal Loss Rate (2010)	5%	30%
Lifetime (years)	13	13

4.6.5 References

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4.7 Medium Stationary Air Conditioning

4.7.1 Overview of Previous Model Assumptions

The medium stationary air conditioning end-use previously used a top-down approach to model HFC consumption and emissions. HFCs were assumed to first enter the market in 1995, growing to a total installed base of 5,912 MT in 2010. Assumptions for the penetration of HFCs entering the market (i.e., installed in newly sold or existing HCFC equipment in a given year) are summarized below.

Table 58. Previous Market Penetrations of HFC Refrigerants into New/Retrofitted Units

	134a	404A	407C	410A	417A*	422D*
1990	25%	-	40%	35%	-	-
2003	10%	3%	70%	15%	2%	-
2007	10%	3%	51%	31%	4%	1%
2008 - 2050	5%	1%	51%	43%	-	-

* R417A and R422D are used to convert R22 equipment.

In the previous model, equipment was assumed to have a lifetime of 13 years. Previous leak rate assumptions for select years are summarized in the table below.

Table 59. Previous HFC Refrigerant Loss Rate Assumptions

Input	1990	2000	2010	2050
Manufacturing Loss Rate	3%	2%	2%	2%
Lifetime Leak Rate	30%	12%	8%	5%
Disposal Loss Rate	10%	8%	5%	4%

4.7.2 End-Use Definition

Includes ducted split, variable refrigerant flow (VRF) non-ducted split, ducted split, and packaged AC systems. Units are used in the commercial UK sector. System cooling capacities typically range from 12 to 30 kW.

4.7.3 Summary of Research Findings and Updates

Equipment Stocks and Growth Rate

Stock Data

BSRIA (2011) indicates that the UK AC market is dominated by commercial applications, with a very small amount of AC in the domestic sector. Using ECODESIGN Lot 10 Draft (2008) stock data for small stationary AC systems—which estimates 4.6 million small stationary AC units in the UK in 2010—and the proportion of BSRIA (2011) sales data for small to medium AC systems—which is approximately 7.3—the medium stationary AC 2010 stock is estimated to be 630,000 units.

These bottom-up estimates were compared with top-down estimates to ensure their reasonableness. Specifically, RTOC (2010) estimates 120 million medium stationary AC units in use worldwide, while Oko-Recherche et al. (2011) estimate there are approximately 32 million units in developed countries. If these estimates were scaled to the UK based on World Bank (2011) GDP data, they would result in a range of 1.7 million (based on Oko-Recherche et al.) to 4.3 million (based on RTOC) units in the UK.

However, given the cooler climate of the UK compared to many other countries, using GDP as a proxy for scaling global or developed country stock estimates likely overestimates stocks in the UK. As such, the 2010 stock of medium AC units in the UK is estimated at 630,000 units, based on consideration of BSRIA data.

Market Growth Rates

BSRIA (2011) provides annual UK sales for various types of medium AC equipment from 2009 to 2014 and estimates the annual change in sales for each of these equipment types. Specifically, annual change between 2009-2014 was estimated to be 2.7% for ducted mini-split, US-style ducted splits, and packed AC systems.

Oko-Recherche et al. (2011) estimate that single-split and multi-split systems in the EU will annually increase by 7% and 5% from 2010-2015, and by 4% and 3% from 2015-2020 respectively. From 2020-2030, the market is not expected to grow. The market for ducted systems is expected to steadily decrease by -0.1% annually from 2010-2030 (Oko-Recherche et al. 2011).

Based on this information, ICF assumes a growth rate of 2.5% from 2010-2015, 1% from 2015-2020, and 0% from 2020 onward. For 1990-2009, historic GDP data from the World Bank (2011) is used to back-cast stock estimates, with any negative growth zeroed-out (given that the recent economic downturn is not believed to have impacted this sector to the same extent as the consumer goods sectors).

Equipment Lifetime

Both EC (2010) and Oko-Recherche et al.(2011) estimate a lifetime of 10 years for multi-split systems and ducted systems in the EU. IPCC (2006) assumes the global average lifetime of between 10 and 20 years for residential and commercial AC systems while IPCC (2000) estimates an average lifetime of 10-15 years. EPEE (2011) estimates the lifetime for EU systems to be between 10 and 15 years for medium AC systems, while SKM Enviros (2011) estimates average lifetime of UK medium AC equipment to be 15 or even 20 years. Based on this information, ICF increased the lifetime from 13 to 15 years based on the EU-specific estimates provided above, which range from 10- 20 years.

Refrigerant Use and Transitions

CFC-12 was phased out of new stationary AC equipment by 1995, which is when HFCs entered the refrigerant market. According to Honeywell (2011), some retrofit activity occurred in the mid/late 2000s (peaking in 2010) to convert HCFC-22 equipment to R-417A (not R-422D). Oko-Recherche et al. (2011) assumes the market is comprised 100% of HFCs in 2010 and projects that by 2020, 1% of the market will use alternatives, reaching 2% by 2050. Honeywell (2011) projects low-GWP HFOs to begin displacing HFC-410A in 2015. SKM Enviros (2011) predicts use of HFO blends in medium stationary AC systems, but not until at least 2015, when HFOs may become available outside of the motor vehicle air conditioning market. EPEE (2011) projects HFC-32 use will increase in later years as a replacement for R-410A.

Based on this information, ICF assumes the market penetrations of refrigerants in new and retrofitted units sold in the UK as shown in the tables below. The percentages in the latter table represent the portion of original refrigerant remaining in eligible equipment (i.e., equipment with 25-75% of its useful life remaining) that is replaced by a retrofit refrigerant.

Table 60. Revised Market Penetration of Refrigerants into New Medium Stationary AC*

Year	12	22	134a	404A	407C	410A	HFO blends	32
1990	60%	40%	-	-	-	-	-	
1995	-	90%	1%	1%	7%	1%	-	
2001	-	-	3%	12%	70%	15%	-	
2010	-	-	-	-	10%	90%	-	
2015	-	-	-	-	-	90%	10%	
2020	-	-	-	-	-	73%	22%	5%
2030	-	-	-	-	-	45%	40%	15%
2050	-	-	-	-	-	25%	40%	35%

* For years not listed, a linear change in market penetration between identified years is assumed.

Table 61. Revised Market Penetrations of Retrofit Refrigerants into Existing Eligible Equipment*

Original	Retrofit	1990–1999	2000	2001	2009	2010	2011- 2050
12	22	-	100%	-	-	-	-
22	417A	-	-	-	-	1%	-

* Eligible equipment for this end-use is defined as equipment with 25-75% of its useful life remaining. Figures are expressed as a percent of total metric tonnes of the remaining original refrigerant installed in existing eligible equipment. A linear change between identified years is assumed.

HFC Charge Size and Loss Rates

Charge Size

For medium stationary AC, Oko-Recherche et al. (2011) estimates a 10.5 to 13.5 kg charge size in the EU. According to one UK industry estimate, this equipment ranges in size between 10-100 kg (Gluckman 2011). IPCC (1996) estimates an average charge range of 2-3 kg for residential air conditioning; while the IPCC (2006) and IPCC (2000) default charge size for all residential and commercial AC is 0.5-100 kg. This information is summarised in the table below.

Table 62. Summary of Charge Size Estimates for Medium Stationary AC

Source	Charge Size Estimate (kg)
Gluckman (2011)	10 – 100
IPCC (2006)	0.5 – 100[a]
IPCC (2000)	0.5 – 100[a]
IPCC (1996)	2 – 3[a]
Oko-Recherche et al. (2011)	10.5 – 13.5

[a] Estimate not specific to medium stationary AC units.

Based on this information, ICF assumes an average charge size of 15 kg, which is slightly higher than the Oko-Recherche et al. estimate for the EU in light of the higher upper bound (of 100 kg) cited for UK equipment by Gluckman (2011). This estimate is also within the IPCC (2006) and IPCC (2000) global default ranges, though higher than the IPCC (1996) range.

Manufacturing Loss Rate

IPCC (1996) estimates an average assembly loss rate of 2-5% for other stationary refrigeration and AC equipment; while the IPCC (2006) and IPCC (2000) default manufacturing loss rates for residential and commercial AC ranges from 0.2-1%. EPEE (2011) estimates the manufacturing loss rate for medium AC systems from 2010 onward is 1% in the EU. ICF assumes a 1% manufacturing loss rate, in line with the EU-specific estimate provided by EPEE (2011).

Operational Loss Rate

According to Oko-Recherche et al. (2011), leak rates for the various medium stationary AC equipment types in the EU are estimated to range from 5-8%. IPCC (1996) estimates an average global annual loss rate of 17% for “other stationary refrigeration and AC equipment.” The IPCC (2006) default leak rate assumption for residential and commercial AC is 1- 10%, while the IPCC (2000) default leak rate assumption is 1-5%.

Based on the EU-specific estimates provided by Oko-Recherche et al. (2011) and recognising the leak checking/repair provisions specified under Regulation (EC) No. 842/2006 on certain fluorinated greenhouse gases (the F-gas Regulation), ICF assumes a loss rate of 6% in 2010, reduced from 8% in 1990 and 2000 due to technology improvements (with a linear decline assumed between 2000 and 2010). The leak rate is assumed to decline linearly from 2010 to reach 5% in 2030, in light of future improvements to technologies and technician service practices. The estimate is outside of the range set out in IPCC (2000) because it is considered that the Oko-Recherche estimate, which is specific to the EU, is more appropriate for the UK.

Disposal Loss Rate

Disposal loss rates for medium AC equipment have been estimated at 70-30% (depending on AC system classification) by Oko-Recherce (2011). IPCC (1996) implies an average disposal loss rate of 18% for “other stationary refrigeration and AC equipment” (assuming up to 90% of the original charge remains at equipment EOL and a recovery efficiency of 80%); while IPCC (2006) implies a rate of 16% for residential and commercial AC equipment (assuming up to 80% of original charge remains at equipment EOL and a recovery efficiency of 80%). IPCC (2000) assumes that 70-80% of the charge remaining at EOL is recoverable. This information is summarised in the table below.

Table 63. Summary of Available Disposal Loss Estimates for Medium Stationary AC

Source	Percent of Original Charge Remaining at EOL	Recovery Efficiency (% of remaining charge that can be recovered)	Estimated Disposal Loss (as % of original charge)
IPCC (1996)	90%	80%	≥18%
IPCC (2000)	NA	70-80%	≤20-30%
IPCC (2006)	80%	80%	≥16%
Oko-Recherche et al. (2011)	NA	NA	70-30%

ICF assumes an average disposal loss rate of 30% in 2010 and a reduced loss rate of 20% by 2030 to reflect higher rates of regulatory compliance and improvements in technology/practices over time (with a linear decline assumed in interim years). Furthermore, ICF assumes a disposal loss rate of 65% in 1990 and 40% in 2000, to reflect the same trends.

Summary

The table below summarises the revised assumptions related to HFC charge size and loss rates.

Table 64. Summary of Charge Size and Loss Rate Assumptions for Medium Stationary AC*

Input	1990	2000	2010	2020	2030-2050
Average HFC Charge Size (kg)	15	15	15	15	15
Manufacturing Loss Rate	2%	2%	1%	1%	1%
Operational Leak Rate	8%	8%	6%	5.5%	5%
Disposal Loss Rate	65%	40%	30%	25%	20%

* For years not listed, a linear change between identified years is assumed.

4.7.4 Summary of Model Updates

The table below summarises the model updates described above for an indicative list of parameters, based on the research conducted.

Table 65. Comparison of Previous vs. Revised Assumptions for Key Parameters

Input	Previous	Revised
Average HFC charge size (kg) for equipment built in 2010	NA	15
Manufacturing Loss Rate (2010)	2%	1%
Operational Leak Rate (2010)	8%	6%
Disposal Loss Rate (2010)	5%	30%
Lifetime (years)	13	15

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4.8 Large Stationary Air Conditioning (Chillers)

4.8.1 Overview of Previous Model Assumptions

The chillers end-use previously used a top-down approach to model HFC consumption and emissions. HFCs were assumed to first enter the market in 1993, growing to a total installed base of 5,396 MT in 2010. Assumptions for the penetration of HFCs entering the market (i.e., installed in newly sold or existing HCFC equipment in a given year) are summarized below.

Table 66. Previous Market Penetrations of HFC Refrigerants into New/Retrofitted Units

	134a	404A	407C	410A	422D*
1990	40%	-	40%	20%	-
2003	42%	5%	50%	3%	-
2007	32%	5%	40%	20%	3%
2008 - 2050	20%	1%	40%	39%	-

* R422D was used to convert R22 equipment

In the previous model, equipment was assumed to have a lifetime of 13 years. Previous leak rate assumptions for select years are summarized in the table below.

Table 67. Previous HFC Refrigerant Loss Rate Assumptions

Input	1990	2000	2010	2050
Manufacturing Loss Rate	1%	1%	1%	1%
Lifetime Leak Rate	10%	5%	3%	3%
Disposal Loss Rate	5%	5%	5%	4%

4.8.2 End-Use Definition

Includes centrifugal, reciprocating, screw, scroll, and absorption chillers, primarily in offices, hotels, shopping centres, and other large buildings, as well as in specialty applications. Cooling capacities can range from less than 100 kW up to 20 MW.

4.8.3 Summary of Research Findings and Updates

Equipment Stocks and Growth Rate

Stock Data

Oko-Recherche et al. (2011) estimate there are 2.8 million chiller units in A2 countries. Based on GDP data from the World Bank (2011), this translates to roughly 140,000 chiller units in the UK. However, according to one representative of a UK chiller manufacturer, there are roughly 40,000 chillers operating in the UK today (McQuay 2011). Based on this input from UK industry representatives, ICF assumes a 2010 stock of 40,000 chillers.

Market Growth Rates

According to one UK chiller manufacturer, there are an estimated 2,500 to 3,000 chillers sold in the UK per year. Growth in the chiller market was 15-20% higher in 2006-2007 than today, prior to the economic slowdown. Moving forward, there may be moderate growth in chillers for data centers and commercial and public sector buildings (McQuay 2011).

BSRIA (2011) provides UK sales of chillers from 2009-2014, for example, 2,883 units sold in 2009 and 3,173 units projected to be sold in 2014; this implies an annual average growth in sales of 1.9% between 2009-2014. EC (2010) projects that the EU-15 chiller market as a whole will increase by 5.5% annually from 2010-2020 and then slow to 2.75% growth annually from 2020 until 2050. Oko-Recherche et al. (2011) estimate a smaller growth of 1% annually from 2010 through 2030 for large and small chillers, and a steady decrease of -1% from 2010-2030 for centrifugal chillers.

Based on this information, ICF assumes a market growth rate of 2% between 2009 and 2015, 1% between 2015 and 2030, and a 0% growth rate from 2030 onward. For 1990-2008, historic GDP data from the World Bank (2011) is used to back-cast stock estimates, with any negative growth zeroed-out (given that the recent economic downturn is not believed to have impacted this sector to the same extent as the consumer goods sectors).

Equipment Lifetime

IPCC (1996) estimates an average lifetime of 15 years for other stationary refrigeration and AC equipment (which includes chillers); while IPCC (2006) provides a default range of 15-30 years for chillers and IPCC (2000) provides a default lifetime of 10-30 years. EC (2010) and Carrier (2008) both estimate a lifetime of 15 years, while Oko-Recherche et al. (2011) estimate an equipment lifetime between 15 and 25 years. One major UK chiller manufacturer estimates an average lifetime of 20 years for larger, well-maintained chillers (Trane 2011); another manufacturer estimates an average lifetime range of 15-20 years for air-cooled chillers, which account for roughly 90% of the UK market and a longer average range of 20-25 years for water-cooled chillers..

ICF assumes an average equipment lifetime of 18 years, which is in line with UK equipment manufacturer estimates and roughly the midpoint for IPCC (2006), IPCC (2000), and Oko-Recherche et al. (2011).

Refrigerant Use and Transitions

According to a leading chiller manufacturer in the UK, CFCs were used in chillers until the early 1990s and mostly transitioned to HCFC-22. By 1996, large chiller manufacturers had transitioned away from HCFC-22 to HFCs, with the full market transitioning by 2000. R-407C was adopted as an interim replacement for HCFC-22 in both small and large chillers, as design requirements were similar; but within 5-7 years, R-407C was primarily replaced by HFC-410A in small chillers (e.g., scroll chillers, which account for the majority of units in the UK) and HFC-134a in large chillers (e.g., centrifugal chillers and large screw chillers), Research and development is currently underway to develop low-GWP HFOs for use in chillers; such systems may be commercialised as early as next year, but it may take up to 10 years before the technology gains a significant market share. Ammonia chillers are and have historically been used in industrial applications; due to cost and safety barriers, this refrigerant is not expected to significantly displace HFC chillers. Chiller retrofits and efficiency upgrades are common in cases where replacement is not physically possible (McQuay 2011).

According to Honeywell, HFC-134a dominates the UK (large) chiller market today accounting for roughly 80% of the market, although ammonia is a key player in industrial chillers applications. In addition, there has been some recent retrofit activity (peaking in 2010) to convert HCFC-22 chillers to R-422D in the UK. Low-GWP HFOs are likely to displace the HFC market starting in 2015-2020 (Honeywell 2011).

One industry representative indicates that there was likely small use of CFC-11 in 1990, although it never experienced widespread use in the UK, and that HCFC-22 was used until 1999 when it experienced a sharp decline. Furthermore, the industry representative estimates that use of R-407C began in 1996 in the UK, while use of R-410A began in 1998. (Gluckman, 2011).

Oko-Recherche et al. (2011) assume that the EU market reached 100% HFCs (HFC-134a, R-407C, and R-410A) in 2000. As the market currently stands, there are very few viable alternative refrigerants for chillers that have comparable performance and energy efficiencies to HFCs (Trane 2011, EarthCare Products 2011). As such, HFCs are expected to continue to dominate the market through 2050, with some penetration of ammonia and hydrocarbons in certain chiller types expected between 2000 and 2030 (EC 2010, Oko-Recherche et al. 2011). According to TEAP (2010), some HCs are in use for smaller chillers (<300 kW) and in some industrial applications; HCs are likely to be used increasingly in small chiller applications in future, once regulations and international standards permit it.

EPEE (2011) projects that HFC-32 will be an important replacement for R-410A, while HFO will be a replacement for HFC-134a. According to SKM Enviros (2011), HFOs will be used in later years (i.e., post 2017) in addition to ammonia.

Based on this information, ICF assumes the following refrigerant transitions into new and retrofitted chillers in the UK, as shown in the tables below. The percentages in the latter table represent the portion of original refrigerant remaining in eligible equipment (i.e., equipment with 25-75% of its useful life remaining) that is replaced by a retrofit refrigerant.

Table 68. Revised Market Penetration of Refrigerants into Large Stationary AC*

Year	11	12	22	134a	407C	410A	717	HFO	32
1990	2%	84%	10%	-	-	-	4%	-	-
1993	-	26%	53%	17%	-	-	4%	-	-
1995	-	-	66%	30%	-	-	4%	-	-
1996	-	-	64%	27%	5%	-	4%	-	-
1998	-	-	38%	35%	18%	5%	4%	-	-
1999	-	-	2%	40%	22%	32%	4%	-	-
2000	-	-	-	40%	23%	33%	4%	-	-
2010	-	-	-	60%	-	35%	5%	-	-
2020	-	-	-	50%	-	20%	5%	20%	5%
2030	-	-	-	25%	-	10%	10%	45%	10%
2050	-	-	-	-	-	-	10%	70%	15%

* For years not listed, a linear change in market penetration between identified years is assumed.

Table 69. Revised Market Penetrations of Retrofit Refrigerants into Existing Eligible Equipment*

Original	Retrofit	1990 – 2004	2010	2014	2015- 2050
22	422D	-	15%	10%	-

* Eligible equipment for this end-use is defined as equipment with 25-75% of its useful life remaining. Figures are expressed as a percent of total metric tonnes of the remaining original refrigerant installed in existing eligible equipment. A linear change between identified years is assumed.

HFC Charge Size and Loss Rates

Charge Size

IPCC (1996) indicates that the average charge size for chillers ranges from 75 to 900 kg; while IPCC (2006) and IPCC (2000) estimate that, depending on equipment type and capacity, the average charge size for chillers can range between 10 and 2,000 kg. According to IIR (2009) the typical HFC chiller charge size is 150 kg. Oko-Recherche et al. (2011) assume an EU charge range for chillers between 35 and 630 kg, with an average charge for large systems of 200 kg. One representative from a major UK chiller manufacturer estimates that average chiller charge size in the UK is 200 kg, typical for a 600-700 kW unit (Trane 2011). Another manufacturer estimates that chillers in the UK range from 30 kg to 1,500 kg, with most falling within the range of 70-300 kg (McQuay 2011). EPEE (2011) estimates that large stationary AC systems in the EU have an average charge size of 160 kg, given the minor share of centrifugal chillers in the EU market. This information is summarized in the table below.

Table 70. Summary of Charge Size Estimates for Large Stationary AC

Source	Charge Size Estimate (kg)
EPEE (2010)	160
IIR (2009)	150
IPCC (2006)	10 – 2,000
IPCC (2000)	10 – 2,000
IPCC (1996)	75 – 900
McQuay (2011)	70 – 300
Oko-Recherche et al. (2011)	35 – 630
Trane (2011)	200

Based on this information, ICF assumes a charge size of 180 kg, which is in line with estimates provided by UK equipment manufacturers and EPEE (which range from 160- 200 kg, on average). This estimate is also within the broad ranges provided by the other sources listed above.

Manufacturing Loss Rate

According to McQuay (2011), UK manufacturing loss rates are lower than 0.5%. IPCC (1996) estimates an average assembly loss rate of 2-5% for other stationary refrigeration and AC equipment (which includes chillers); while IPCC (2006) and IPCC (2000) estimate the manufacturing loss for chillers to be between 0.2% and 1%. ICF assumes a 0.5% manufacturing loss rate, in line with the UK-specific estimate provided by McQuay (2011) and within the default range provided by IPCC (2006, 2000).

Operational Loss Rate

McQuay (2011) estimates an operational loss rate of 2-3% for chillers in the UK, while Carrier (2008) estimates a 3% leak rate for chillers globally, IIR (2009) estimates a loss rate of 4%, and Oko-Recherche et al. (2011) assume 5% for chillers in the EU. IPCC (1996) estimates an average annual loss rate of 17% for other stationary refrigeration and AC equipment (which includes chillers), while the IPCC (2006) and IPCC (2000) default leak rate is between 2% and 15%.

Based on this information, ICF maintains the previous loss rate assumption of 3% in 2010. This estimate aligns with the upper bound estimate for UK chillers provided by McQuay (2011), which is believed to be appropriate given the higher leak estimate for the EU provided by Oko-Recherhe et al., as well as the global estimates provided by Carrier and IIR. By 2020, ICF assumes the annual loss rate decreases to 2% due to improved refrigerant retention rates and technician practice/knowledge (with a linear decline assumed in intervening years).

Disposal Loss Rate

According to Gluckman (2011), disposal losses from large equipment in the UK are low because refrigerant recovery occurs on-site. Specifically, Gluckman estimates that >95% of the charge remains at EOL with a recovery efficiency of 95%; this implies a disposal loss rate of less than 5%. According to another UK industry representative in the disposal sector, most refrigerant recovery from large commercial chillers occurs on-site; however, based on remote units that are degassed offsite at disposal, only about 60% of the original charge is typically recovered at the time of disposal (Overton Recycling 2011); this implies that at most 40% is emitted prior to or during disposal. According to McQuay (2011), specialist recycling companies dispose of chiller equipment and are generally reliable in the UK, but a disposal loss rate as high as 30% could be reflective of the entire market—though this loss rate will continue to decline over time.

For EU disposal loss estimates, EC (2010) assumes a disposal loss rate of at least 4% for chillers (based on the assumption that 70% of the charge remains at EOL and 95% is technically recoverable), while Oko-Recherche et al. (2011) assume a loss rate of 30%.

For global disposal loss estimates, the IPCC (1996) implies an average disposal loss rate of 18% for other stationary refrigeration and AC equipment, including chillers (assuming up to 90% of the original charge remains at equipment EOL and a recovery efficiency of 80%); while IPCC (2006) provides a range of 16-20% (assuming 80-100% of the original charge remains at equipment EOL and a recovery efficiency of 80%). The IPCC (2000) assumes that 80-95% of charge remaining at EOL is recoverable. This information is summarised in the table below.

Table 71. Summary of Available Disposal Loss Estimates for Large Stationary AC

Source	Percent of Original Charge Remaining at EOL	Recovery Efficiency (% of remaining charge that can be recovered)	Estimated Disposal Loss (as % of original charge)
EC (2010)	70%	95%	>4%
Gluckman (2011)	>95%	95%	≤5%
IPCC (1996)	90%	80%	≥18%
IPCC (2000)	NA	80-95%	≤5-20%
IPCC (2006)	80-100%	80%	≥16-20%
McQuay (2011)	NA	NA	30%
Oko-Recherche et al. (2011)	NA	NA	30%
Overton Recycling (2011)	NA	NA	≤40%

Based on this information, ICF assumes a disposal loss rate of 20% in 2010, reaching 15% by 2020 and 10% by 2030. In earlier years, ICF assumes a higher disposal loss rate (i.e., 30% in 2000 and 50% in 1990). The higher rate accounts for losses likely to occur during the recovery process as well as potential non-compliance with refrigerant recovery requirements. Rates are assumed to decrease over time, as technology and technician practice/knowledge improves.

Summary

The table below summarises the revised assumptions related to HFC charge size and loss rates.

Table 72. Summary of Revised Charge Size and Loss Rate Assumptions for Large Stationary AC*

Input	1990	2000	2010	2020	2030-2050
Average HFC Charge Size (kg)	180	180	180	180	180
Manufacturing Loss Rate	0.5%	0.5%	0.5%	0.5%	0.5%
Operational Loss Rate	3%	3%	3%	2%	2%
Disposal Loss Rate	50%	30%	20%	15%	10%

* For years not listed, a linear change between identified years is assumed.

4.8.4 Summary of Model Updates

The table below summarises the model updates described above for an indicative list of parameters, based on the research conducted.

Table 73. Comparison of Previous vs. Revised Assumptions for Key Parameters

Input	Previous	Revised
Average HFC charge size (kg) for equipment built in 2010	NA	180
Manufacturing Loss Rate (2010)	1%	2%
Operational Loss Rate (2010)	3%	3%
Disposal Loss Rate (2010)	5%	20%
Lifetime (years)	13	18

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4.9 Heat Pumps

4.9.1 Overview of Previous Model Assumptions

No end-use previously existed in the model to account for heat pump systems.

4.9.2 End-Use Definition

Heat pumps used for residential (typically <20 kW capacity) and small commercial (typically >20 kW capacity) applications, including air-source heat pumps (ASHP) (i.e., air-to-water systems) and ground-source heat pumps (GSHP) (i.e., water-to-water and ground-to-water systems).

4.9.3 Summary of Research Findings and Updates

Equipment Stocks and Growth Rate

Stocks

AEA (2010) estimates that in 2008 there were 3,415 GSHPs and 169 ASHPs installed in the UK, +/- 25%. However, based on more recent information from BSRIA (2011a), there were 16,455 heat pumps with capacities of up to 20 kW in 2009 and 18,400 units by 2010 (including 3,590 GSHP units and 14,890 ASHP units) (BSRIA 2011a). According to BSRIA (2011a), use of heat pumps with capacities of up to 20 kW began in the UK in 2005 at roughly 750 units and increased sharply in recent years. Heat pumps of this capacity are used primarily in the domestic sector. According to one industry representative, the number of heat pumps in the UK with capacities of over 20 kW (primarily used in the commercial sector) was approximately 520 units in 2008 (BSRIA, 2011c). Strong growth in heat pumps in the UK is expected to continue over the next few years in response to DECC's Renewable Heat Incentive (RHI) Scheme;[10] by 2014, an estimated 45,000 heat pumps with capacities of up to 20 kW will be installed (Danfoss 2011a). Historically, ground source heat pumps (GSHPs) were installed in greater numbers than ASHPs in the UK, but use of ASHPs is expected to increase significantly over GSHPs moving forward (Danfoss 2011a).

In terms of historical stocks, Fawcett (2011) estimates that sales of GSHP systems in the UK were: 1,000 units in 2005/2006; 3,000 units in 2007; 5,000 units in 2008; and 8,000 units in 2009. Oko-Recherche et al. (2011) estimate that there were 1.5 million HFC-containing heat pump units across the EU-27 in 2010. Based on data from BSRIA (2008), France and Germany are believed to account for the greatest share of EU-27 heat pump consumption, since China, France, Sweden, and Germany were reported as collectively holding 82% of the heat pump market by volume in 2007. To put the magnitude of global heat pump sales into perspective, the Heat Pump Center (2011) reports that over 1 million heat pumps are in operation in Sweden today.

Based on the most recent information from BSRIA (2011a, c) and Fawcett (2011), ICF assumes that heat pumps entered the UK market in 2005. Based on BSRIA (2011a) and Danfoss (2011a), ICF assumes the stock of heat pumps with capacities of up to 20 kW was roughly 750 units in 2005, reaching 16,455 units in 2009, 18,400 units in 2010, and 45,000 units in 2014.

For units with capacities above 20 kW, BSRIA (2011c) estimated UK stocks in 2008 at 520 units. Based on the implied growth rates from BSRIA (2011a) and Danfoss (2011a), ICF assumes the stock of heat pumps with capacities over 20 kW reached 1,870 units in 2010. Based on data from BSRIA (2011a), ICF assumes that ASHPs account for 80% of the UK heat pump market, with GSHPs accounting for 20%.

Additionally, ICF assumes that 85% of all heat pumps are manufactured pre-charged outside the UK, based on anecdotal information (Danfoss 2011b, Gluckman 2011).

[10] On 10 March 2011, the UK Government announced the details of the Renewable Heat Incentive policy aimed at providing long-term financial support to renewable heat installations to encourage the uptake of renewable heat. The scheme will be introduced in two phases; in the first phase, long-term tariff support will be targeted in the non-domestic sectors (i.e., industrial, business and public sector); in the second phase, the scheme will be expanded to include more technologies as well as support for households. (DECC 2011)

Market Growth Rates

RTOC (2011) assumes that the total number of heat pumps installed in the EU will grow by a factor of 16 between 2008 and 2030, which implies an average annual growth rate of roughly 13% per year from 2008 to 2030. Based on the historical and projected UK stock data provided by Danfoss and BSRIA (2011a), from 2005 to 2010 the implied growth rate is approximately 90% per year; and from 2010-2014, the projected growth rate is roughly 25% per year. Furthermore, BSRIA (2011a) projects that the UK heat pump market will grow at two-digit rates in the future, driven primarily by ASHPs. One industry representative projects that heat pump usage in the UK will grow to reach approximately 1 million installed units by 2030, which implies roughly a 21% growth rate from 2015-2030 (SKM Enviros 2011).

Based on this information, ICF assumes historical growth of 90% per year from 2005-2010, 25% per year from 2010-2014, and 20% per year from 2015-2030 for both heat pumps with capacities of <20 kW and >20 kW. These ambitious growth rates are appropriate in light of the RHI Scheme, introduced in March 2011, through which DECC is promoting the use of several forms of heat pumps. Moreover, these ambitious growth rates are believed to be reasonable given the high projected growth for English households alone—estimated at 27% from 2008-2033, or an increase of 232,000 households per year (Communities and Local Government 2010). Although growth in the heat pump market may continue beyond 2030, ICF conservatively assumes zero growth from 2030-2050.

Equipment Lifetime

Danfoss (2011a) indicated that 15 years is a reasonable average lifetime but noted there will be variations based on type of equipment (i.e., air- versus ground-source) and geographic location. For example, GSHPs may last considerably longer than 15 years. Oko-Recherche et al. (2011) also estimate an average equipment lifetime of 15 years for heat pumps. IPCC (1996) estimates an average equipment lifetime of 15 years for other stationary refrigeration and AC equipment. IPCC (2006) provides a default lifetime for residential and commercial AC equipment, including heat pumps, of 10-20 years, while IPCC (2000) provides a default lifetime of 10-15 years. Based on this information, ICF assumes an average lifetime of 15 years for heat pump equipment. It should be noted that this lifetime is not assumed to apply to the ground loop—which will last for considerably longer than 15 years.

Refrigerant Use and Transitions

According to RTOC (2011), most heat pump systems worldwide historically relied on HCFC-22. With implementation of the Montreal Protocol, blends of HFC have been used as alternatives. R-410A has been used in new equipment and R-407C has been used for retrofit equipment in some parts of Europe. Until 2004, nearly 50% of heat pumps sold in the EU used HC-290, but use of HC-290 has since declined due to the introduction of the Pressure Equipment Directive (PED) (RTOC 2011). Similarly, Oko-Recherche et al. (2011) indicate that R-290 or R-1270 had been used in the 1990s and 2000s when CFCs were banned (i.e., R-502), but that the majority of production was stopped due to the PED and that use of HFC blends (R-407C, R-404A, and R-410A) have since taken over. Oko-Recherche et al. also indicate that today some heat pumps using HCs (R-290, R-600a) and CO_2 are available for capacities less than 20 kW, and that HFO-1234yf or HFC-32 could also be used in the future.

However, because heat pumps did not significantly penetrate the UK market until 2005, it is reasonable to assume that only HFC heat pumps are currently installed. This assumption is supported by input from Danfoss (2011a), which indicated that the primary refrigerants used in UK heat pumps are R-407C and R-410A, in addition to a small share of HFC-134a and R-404A. AEA (2010) estimates that GSHPs in the UK are likely to use HFC-134a, and projects future alternatives to include HCs and/or CO_2. Indeed, at least one manufacturer manufactures CO_2 heat pumps (up to 4.5 kW) for the Japanese market and is piloting such systems for the French market with plans to tackle the UK market next (Sanden 2011). According to Honeywell (2011), R-410A is the most common refrigerant in GSHPs, with R-407C dominating the ASHP market. Over the next 10 years or so, low-GWP HFOs are expected to begin displacing the HFC market (Honeywell 2011).

BSRIA (2011b) indicates that ground source heat pumps typically use R-407C or R-410A, while R-410A is the most common refrigerant for air-to-water heat pumps.

Additionally, OkoRecherche (2011) estimates that from 2000 onwards, HFC blends have been used in heat pump equipment in the EU. Specifically, R-407C, R-404A (prior to 2008), and an increasing use of R-410A have been or are being used. Oko-Recherche et al. estimate the specific HFC-refrigerant split for new-installed heat pumps from 2000 to 2009, as summarised in the table below.

Table 74. HFCs Installed in EU Heat Pumps, as Estimated by Oko-Recherche et al. (2011)

Year	404A	407C	410A
2000	20%	80%	0%
2009	0%	30%	70%

Based on the above information, ICF assumes the market penetration rates of refrigerants in new heat pump units sold in the UK as presented in Table 75. As shown, R-410A is assumed to dominate the market, followed by R- 407C (based on BSRIA [2011b]). ICF assumes that over time, as there is an increasing political push and technical ability to adopt low-GWP alternatives, HCs will account for an increasing market share.

Table 75. Revised Market Penetration of Refrigerants into New Heat Pump Equipment*

Year	404A	407C	410A	134a	HCs	CO_2	HFOs
1990-2004	-	-	-	-	-	-	-
2005	4%	44%	50%	2%	-	-	-
2010	2%	30%	66%	2%	-	-	-
2015	-	20%	80%	-	-	-	-
2020	-	10%	70%	-	5%	1%	14%
2030	-	-	30%	-	20%	5%	45%
2050	-	-	10%	-	30%	10%	50%

* For years not listed, a linear change in market penetration between identified years is assumed.

HFC Charge Size and Loss Rates

Charge Size

AEA (2010) estimates an average HFC-134a charge size of 2 kg for GSHPs in the UK. Oko-Recherche et al. (2011) estimate that EU heat pump systems are 2.6 kg on average, with a small percentage of the systems charged with 3.0 kg. EPEE (2011) assumes an average EU charge size of 2.5 kg for ASHPs and 15 kg for GSHP. IPCC (2006) and IPCC (2000) estimate that the charge size for residential and commercial air conditioners, including heat pumps, is between 0.5 and 100 kg; IPCC (1996) does not specifically estimate a charge size for heat pumps. This information is summarized in the table below.

Table 76. Summary of Charge Size Estimates for Heat Pumps

Source	Charge Size Estimate (kg)
AEA (2010)	2
EPEE (2011)	2.5 (ASHP) 15 (GSHP)
IPCC (2006)	0.5 – 100[a]
IPCC (2000)	0.5 – 100[a]
Oko-Recherche et al. (2011)	2.6 – 3.0

[a] Estimate not specific to heat pumps

Based on the above information, and assuming domestic heat pumps (i.e., smaller heat pumps) account for approximately 90% of the total UK heat pump market in 2010 (based on BSRIA, 2011c), with ASHPs accounting for 80% of the total market, ICF assumes a weighted average charge size of 3 kg.

Manufacturing Loss

The IPCC (1996) estimates an average assembly loss of 2-5% for other stationary refrigeration and AC equipment, while IPCC (2006) and IPCC (2000) provide a default manufacturing loss rate of 0.2-1% for residential and commercial AC systems, including heat pumps. ICF assumes a loss rate of 1%—consistent with the upper-bound estimate provided by IPCC (2000).

Operation Loss

Oko-Recherche et al. (2011) estimate an operation loss rate of 3.5% for heat pumps in the EU. One UK industry representative suggests a 5% leak rate may be more realistic (Gluckman 2011). The IPCC (1996) does not provide a specific leak rate for heat pumps, but estimates a 17% annual leak rate for "other stationary refrigeration and AC equipment," which includes heat pumps. The IPCC (2006) default range for "residential and commercial AC systems including heat pumps" is 1-10% while the IPCC (2000) default range is 1-5%. According to Johnson (2010a), a peer-reviewed paper, the average operation loss rate for heat pumps is roughly 6% per year.

Based on this information, ICF assumes an operation loss rate of 6% from 2005-2030, which is conservatively in line with UK industry estimates (i.e., SKM Enviros 2011), peer reviewed literature (i.e., Johnson, 2011), and roughly the mid-point of the IPCC (2006) range. However, ICF assumes a reduced leak rate of 3.5% by 2030, to reflect technological improvements made over time.

Disposal Loss

EC (2010) assumes that small stationary AC equipment, including heat pumps, have 90% of charge remaining at disposal with 90% of that charge technically recoverable; thus, assuming full compliance with refrigerant recovery requirements, this implies a loss rate of 9%. Oko-Recherche et al. (2011) assume a disposal loss rate of 35% for heat pumps. IPCC (1996) implies an average disposal loss rate of 18% for other stationary refrigeration and AC equipment (assuming up to 90% of the original charge remains at equipment EOL and a recovery efficiency of 80%); while IPCC (2006) assumes a loss rate of roughly 16% for residential and commercial AC equipment including heat pumps—assuming that up to 80% of initial charge remains at EOL and a recovery efficiency of up to 80%. IPCC (2000) assumes that 70-80% of the charge remaining at EOL is recoverable. According to the peer-reviewed paper by Johnson (2011) the disposal loss rate for developed countries is estimated at roughly 55% (Johnson, 2011). This information is summarised in the table below.

Table 77. Summary of Available Disposal Loss Estimates for Heat Pumps

Source	Percent of Original Charge Remaining at EOL	Recovery Efficiency (% of remaining charge that can be recovered)	Estimated Disposal Loss (as % of original charge)
EC (2010)	90%	90%	>9%
Johnson (2011)	NA	NA	55%
IPCC (1996)	90%	80%	≥18%
IPCC (2000)	NA	70-80%	≤20-30%
IPCC (2006)	80%	80%	≥16%
Oko-Recherche et al. (2011)	NA	NA	35%

Based on this information, ICF assumes a disposal loss rate of 35% from 2005-2030, and slightly lower rates of 20% by 2020 and 15% by 2030 as EOL recovery technology and technician compliance/ practices are likely to improve over time. Although the 35% assumption in 2010 is outside of the IPCC (2000) range, it is consistent with the EU estimate provided by Oko-Recherche et al. (2011), and slightly lower than the estimate for all developed countries provided by Johnson (2011).

Summary

The table below summarises the key assumptions for heat pumps.

Table 78. Summary of Key Assumptions for Heat Pumps*

Input	1990-2004	2005	2010	2020	2030-2050
Average HFC Charge Size (kg)	NA	3	3	3	3
Manufacturing Loss Rate	NA	1%	1%	1%	1%
Operational Loss Rate	NA	6%	6%	6%	3.5%
Disposal Loss Rate	NA	35%	35%	20%	15%
Lifetime (years)	15				

*For years not listed, a linear change between identified years is assumed.
**85% of units assumed to be manufactured pre-charged outside UK.

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4.10 Land Transport Refrigeration

4.10.1 Overview of Previous Model Assumptions

The transport refrigeration end-use previously used a top down approach to model HFC consumption and emissions. HFCs were assumed to first enter the market in 1994, growing to a total installed base of 579 MT in 2010. Assumptions for the penetration of HFCs entering the market in new or existing (retrofit equipment are summarized below.

Table 79. Previous Market Penetrations of HFC Refrigerants into New/Retrofitted Units

	134a	404A	410A	507
1990	30%	60%	-	10%
2003	18%	80%	2%	-
2007	16%	82%	2%	-
2008 - 2050	16%	82%	2%	-

In the previous model, equipment was assumed to have a lifetime of 8 years. Previous refrigerant loss rate assumptions for select years are summarized in the table below.

Table 80. Previous HFC Refrigerant Loss Rate Assumptions

Input	1990	2010	2050
Manufacturing Loss Rate	1%	1%	1%
Lifetime Leak Rate	15%	8%	5%
Disposal Loss Rate	15%	5%	4%

4.10.2 End-Use Definition

Includes refrigerated road vehicles (i.e., light commercial vehicles, trucks, trailers) and intermodal containers.

4.10.3 Summary of Research Findings and Updates

Equipment Stocks and Growth Rate

Stock Data

The stock of land transport refrigeration units in the UK can be estimated based on input from industry stakeholders, due to lack of UK-specific information in published literature. One major manufacturer of transport refrigeration equipment in Europe estimates that the UK's fleet of refrigerated road vehicles in 2009 was approximately 80,000 to 90,000 vehicles, of which approximately 25% were trailers, 10-12% were trucks, and 60-65% were light commercial (i.e., small trucks and vans). Furthermore, the manufacturer indicated that road vehicles account for the vast majority of the refrigerated transport market in the UK, estimating that the 2010 intermodal container fleet does not exceed 500 units (CBI 2011). These stock estimates suggest that refrigerated road vehicles (at 85,000 units) account for approximately 99% of the UK's land transport refrigeration market while intermodal containers represent approximately 1% of the market. Similarly, input from Mexichem Fluor indicates that intermodal containers represent a very small portion of the market and that emissions from this mode are insignificant. Rather, the focus for emissions estimation should be given to trucks and delivery vans (Mexichem Fluor, 2011).

ICF estimates that the total stock of land transport refrigeration units in the UK in 2009 was 85,000 based on the estimated 2009 road vehicle stock of units—assuming this figure represents 99% of the market, with an additional 500 intermodal container units representing approximately 1% of the market. ICF further assumes that 25% of the 2009 road vehicles are trailers (21,250), 11% are trucks (9,350), and 64% are light commercial (55,250).

Market Growth Rates

The market growth rates for the transport refrigeration market in the UK can be estimated based on input from industry stakeholders coupled with published information in EC (2010) and Oko-Recherche et al. (2011).

One major manufacturer of transport refrigeration equipment in Europe reports that there was strong historical growth in the market for refrigerated road vehicles between 2005 and 2008, followed by a significant market decline in 2008 and 2009 due to the global economic downturn but that the market today is beginning to recover. Furthermore, the manufacturer projects the market to grow between 7-9% in the next three to five years (as the market rebounds), but beyond that steady growth is projected in line with natural growth in GDP (CBI 2011).

Oko-Recherche et al. (2011) project that the transport refrigeration market in the EU (including road, rail, and intermodal containers) will increase by 2.5% by 2030. EC (2010) projects that market growth in the transport refrigeration sector (also including road, rail, and intermodal containers) will increase by 6% per year from 2010-2020 and 4% per year from 2021-2050 in the EU-15.

According to Honeywell (2011a), the market growth rate will be higher than 1.5% per year through 2015 given a rapidly developing home delivery business in the UK.

Based on the above information, ICF assumes a growth rate of 2% per year from 2009-2015, in line with estimates from UK industry representatives. From 2015-2030, ICF assumes a growth rate of roughly 0.5% per year, based on estimates from Oko-Recherche et al. (2011). ICF assumes a growth rate of 0% from 2030 to 2050. For 1990-2008, historic GDP data from the World Bank (2011) is used to back-cast stock estimates.

Equipment Lifetime

Equipment lifetime estimates for land transport refrigeration vary in the literature. RTOC (2010) estimates the average lifetime of refrigerated road vehicles, railcars, and intermodal containers to be between 10 to 15 years but less than 10 years if the equipment is used intensively. IPCC (2006) and IPCC (2000) estimate a range of 6-9 years, and EC (2010) estimates an average of 14 years.

Input from one major manufacturer of refrigerated transport equipment in Europe suggests that the average lifetime for refrigerated trailers and trucks in the UK can range from 5 to 8 years for the “first life” with a possible “second life” of approximately 2 years. For light commercial vehicles (i.e., small trucks/vans), the manufacturer estimates a lifetime of 4 to 7 years (CBI 2011). Assuming the UK refrigerated transport market is 64% light commercial vehicles and 36% trucks/trailers, the weighted average lifetime based on these estimates would be over 6 years.

Based on the above information, ICF assumes an average lifetime of 7 years.

Refrigerant Use and Transitions

According to Honeywell, CFC-12 and R-502 were historically used in land transport refrigeration, with HCFC-22 taking over the market due to the CFC phaseout. HFC-134a and -404A began penetrating the UK market in the mid/late 1990s to displace HCFC-22. Moving forward, R-407F will serve as an interim replacement for these HFCs, until low-GWP HFOs and CO_2 become viable. (Honeywell 2011b)

Oko-Recherche et al. (2011) estimate that the majority of refrigerant installed in refrigerated vans in 1995 was CFC-12 (88%), which was fully replaced by HFC-134a by 2003. The report further estimates that 100% of the trucks/trailers in operation were charged with HCFC-22 in 1995, which was fully replaced by R-404A by 2009. The report also estimates that new road transport refrigeration units are typically charged with HFC-134a or R-404A, though some R-410A and R-407C is also used.

Industry sources also provided information on refrigerant use in this end-use. Specifically, Mexichem Fluor (2011) estimates that R-404A is the primary refrigerant of choice worldwide for road transport refrigeration. One major manufacturer of transport refrigeration equipment in Europe indicated that R-404A is primarily used in UK truck/trailer applications and that either R-404A (60%) or R-134a (40%) are used in light commercial applications; these two refrigerants (R-404A and R-134a) are estimated to account for 90% or more of the market. The manufacturer also indicated that there has been limited use of CO_2 in open-loop cryogenic systems in the UK (and limited use of R-410A combined with HC-290 in other European countries), but these low-GWP alternatives have not yet gained any significant market penetration in the UK. The manufacturer expects that the refrigerant mix will remain fairly constant over the next 5-10 years, but suspects that future legislation and R&D efforts will lead to new low-GWP refrigerant alternatives (such as HFO-1234yf) being used beyond that time (CBI 2011)

One industry representative projects that R-407F or R-407A may be used beginning as early as 2015 in place of R-404A, and that by 2020 HFO/HFC blends may begin to penetrate the market (Gluckman, 2011). Honeywell (2011a) projects that there will be no more use of R-404A by 2030, with HFOs dominating the market with some CO_2.

Based on this information, the table below summarises the market penetrations of refrigerants into new land transport refrigeration vehicles for key years.

Table 81. Revised Market Penetration of Refrigerants into New Land Transport Refrigeration Units*

Year	12	502	22	134a	404A	407F	744	HFOs/ Low-GWP HFCs
1990-1993	40%	40%	20%	-	-	-	-	-
1994	-	-	65%	10%	25	-	-	-
2000	-	-	5%	15%	80%			
2001	-	-	-	15%	85%	-	-	-
2010	-	-	-	15%	85%	-	-	-
2015	-	-	-	15%	80%	5%	-	-
2020	-	-	-	10%	44%	40%	1%	5%
2030	-	-	-	-	-	40%	20%	40%
2050	-	-	-	-	-	-	10%	90%

* For years not listed, a linear change in market penetration between identified years is assumed.

HFC Charge Size and Loss Rates

Charge Size

RTOC (2010) and Oko-Recherche et al. (2011) both estimate that the average charge size in refrigerated trailers is about 7.5 kg. For refrigerated trucks, RTOC estimates a range from 2-6 kg while Oko-Recherche et al. estimate approximately 4 kg. EC (2010) estimates an average HFC charge of 4.5 kg for all land transport refrigeration equipment. For intermodal containers, RTOC (2011) estimates an average of 4.5 kg.

These estimates are in line with the input from one major manufacturer of road transport refrigeration equipment in Europe, who estimates a range of approximately 3-6 kg for new refrigerated trucks, between 5-7.5 kg for new refrigerated trailers, and between 0.8-1 kg for new light commercial vehicles. The manufacturer indicated that these charge sizes have decreased significantly over the last few years, and predicts that they may decrease slightly more in future due to technology improvements and market pressure (i.e., mimicking competitors' efforts to reduce charge size, cost savings associated with refrigerant). The manufacturer also indicated that the charge sizes of their equipment are slightly lower than the industry average (CBI 2011). The weighted average of these estimates (assuming 7.5 kg for trailers, 6 kg for trucks, 1 kg for small commercial vehicles, and 4.5 kg for intermodal containers) is approximately 3 kg.

IPCC (1996) provides an estimate of 8 kg for transport refrigeration sector, including trucks, trains and ships with refrigerated compartments. However, since this definition includes refrigerated ships, the estimated charge size is likely to be an overestimate for land transport refrigeration units. IPCC (2006) and IPCC (2000) estimate a range of 3 - 8 kg for the full range of transport refrigeration equipment, including trucks, containers, reefers, and wagons. This information is summarized in the table below.

Table 82. Summary of Charge Size Estimates for Land Transport Refrigeration

Source	Charge Size Estimate (kg)
EC (2010)	4.5
IPCC (2006)	3 – 8
IPCC (2000)	3 – 8
IPCC (1996)	8
Oko-Recherche et al. (2011)	4, 7.5
RTOC (2010)	2 – 6, 7.5
ThermoKing (2011a, 2011b)	1 – 7.5

Based on the information above, ICF assumes a weighted average HFC charge size of 4 kg. Prior to 2005, ICF assumes an HFC charge size of 4.5 kg. Beyond 2010, ICF assumes the charge size will continue to decline linearly to reach 3 kg by 2030. The 4 kg estimate is in line with the EU estimate provided by Oko-Recherche et al. and the mid-range of the RTOC estimate; it is also higher than the average estimate provided by a leading manufacturer (i.e., 3 kg) that acknowledged their equipment charge size to be smaller than most.

Manufacturing Loss Rate

IPCC (1996) estimates an average assembly loss rate of 2-5% for other stationary refrigeration and AC equipment (which includes transport refrigeration); IPCC (2006) and IPCC (2000) estimate a manufacturing loss rate range of 0.2-1% for the transport refrigeration sector specifically. One major manufacturer of transport refrigeration equipment in the UK indicated that their manufacturing loss rates are negligible, and that refrigerant leaks seldom occur when vehicles are initially charged during manufacture. However, the manufacturer indicated that their rate may be lower than the industry average (CBI 2011).

ICF assumes an average manufacturing loss rate of 0.2% (the low end of the IPCC 2006 range and consistent with information from UK manufacturers) for land transport refrigeration equipment in the UK.

Operation Loss Rate

According to one leading UK manufacturer of transport refrigeration equipment, the average annual operation loss rate for units under warranty is roughly 1.3% per year for the first 1-3 years of equipment life; over the lifetime of the units, the average annual leak rate may be as high as 5% for units produced by this manufacturer, although the industry average is likely to be higher (CBI 2011). However, according to another UK equipment manufacturer, an average annual leak of 15% is reasonable, given the constant movement and impact to which land transport refrigeration systems are exposed, which makes them prone to leakage (United Technologies 2011). United Technologies (2011) underscores that such refrigeration systems are well maintained to ensure optimal operation, given the high value of goods that they contain.

Across the EU, EPEE (2011) estimates an average leak rate of 15-25% for refrigerated trucks, while Oko-Recherche et al. (2011) estimate 20%.

RTOC (2010) estimates an operation loss rate of 10-30% from refrigerated road vehicles. IPCC (1996) estimates an average annual loss rate of 17% for other stationary refrigeration and AC equipment (which includes transport refrigeration); the IPCC (2006) and IPCC (2000) default operation loss rate for all modes of transport refrigeration equipment is 15-50%, while a range of 15-32% was reported by other parties (UNFCCC 2011).

Based on this information, ICF assumes an operation loss rate of 15% in 2010, which is slightly lower than the EU estimates provided by Oko-Recherche et al. and EPEE, but within the IPCC (2006) and IPCC (2000) default ranges; the lower rate accounts for UK-specific industry information provided by a leading UK manufacturer (CBI 2011). ICF assumes that this loss rate was significantly higher in 1990 (30%), and that it will continue to decrease over time, reaching 10% by 2030, as technological improvements are made.

Disposal Loss Rate

Oko-Recherche et al. (2011) estimate a disposal loss rate of approximately 30% for refrigerated road vehicles in Europe. EC (2010) estimates that the disposal loss rate in EU-15 countries is approximately 7%—based on the assumptions that 70% of original charge remains at equipment EOL and 90% of that amount is technically recoverable (assuming 100% compliance with refrigerant recovery requirements). IPCC (1996) indicates an average disposal loss rate of 18% for other stationary refrigeration and AC equipment, including transport refrigeration (assuming up to 90% of the original charge remains at equipment EOL and a recovery efficiency of 80%). IPCC (2006) provides a default disposal loss range for transport refrigeration equipment of 15% (assuming up to 50% of the original charge remains at equipment EOL and a recovery efficiency of 70%). IPCC (2000) estimates that 70-80% of the charge remaining at EOL is recoverable.

According to one major manufacturer of road transport refrigeration equipment in Europe, UK trailers/trucks are often exported to Eastern Europe or the Middle East at equipment EOL for resale. For those vehicles that remain in the UK, compliance with refrigerant recovery regulations are believed to be very high. According to a representative of a leading UK manufacturer, roughly 15% of the original charge may be emitted on average at disposal (CBI 2011). This information is summarised in the table below.

Table 83. Summary of Available Disposal Loss Estimates for Land Transport Refrigeration

Source	Percent of Original Charge Remaining at EOL	Recovery Efficiency (% of remaining charge that can be recovered)	Estimated Disposal Loss (as % of original charge)
EC (2010)	70%	90%	>7%
IPCC (1996)	90%	80%	≥18%
IPCC (2000)	NA	70-80%	≤20-30%
IPCC (2006)	50%	70%	≥15%
Oko-Recherche et al. (2011)	NA	NA	30%
CBI (2011)	NA	NA	15%

Based on this information, ICF assumes an average disposal loss rate of 20% in the UK in 2010. This estimate is within the range provided for the UK by a system manufacturer and that provided for the EU by Oko-Recherche. Furthermore, ICF assumes higher losses in historical years (i.e., 50% in 1990 and 35% in 2000), and lower losses in future years (i.e., 15% by 2020 and 10% by 2030) in response to increased compliance with refrigerant recovery regulations over time, as well as improved recovery technologies and technician practices. Because stock estimates do not account for any export of equipment at end-of-life (e.g., resale to Eastern Europe or the Middle East), disposal emissions in the UK may be over-estimated; additional research is needed to explore this further.

Summary

The table below summarises the revised assumptions related to HFC charge size and loss rates.

Table 84. Summary of Revised Charge Size and Loss Rate Assumptions for Land Transport Refrigeration*

Input	1990	2000	2010	2020	2030-2050
Average HFC Charge Size (kg)	4.5	4.5	4	3.5	3
Manufacturing Loss Rate	0.2%	0.2%	0.2%	0.2%	0.2%
Operational Loss Rate	30%	25%	15%	12.5%	10%
Disposal Loss Rate	50%	35%	20%	15%	10%

*For years not listed, a linear change between identified years is assumed.

4.10.4 Summary of Model Updates

The table below summarises the model updates described above for an indicative list of parameters, based on the research conducted.

Table 85.Comparison of Previous vs. Revised Assumptions for Key Parameters

Input	Previous	Revised
Average HFC charge size (kg) for equipment built in 2010	NA	4
Manufacturing Loss Rate (2010)	1%	0.2%
Operational Loss Rate (2010)	8%	15%
Disposal Loss Rate (2010)	5%	20%

Lifetime (years)	8	7

4.10.5 References

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4.11 Marine Transport Refrigeration

4.11.1 Overview of Previous Model Assumptions

No end-use previously existed in the model to account for marine transport refrigeration.

4.11.2 End-Use Definition

Refrigerated fishing vessels (18 meters in length and above) used for domestic (i.e., UK port-to-port) transport.[11]

4.11.3 Summary of Research Findings and Updates

Equipment Stocks and Growth Rate

Stock Data

Oko-Recherche et al. (2011) assume that fishing vessels over 18 meters in length contain refrigeration systems. The UK Marine Management Organisation (UK MMO 2010) estimates that there were approximately 527 registered and licensed fishing vessels over 18 meters in length in the UK as of December 2010 out of 6,477 total vessels of all sizes (i.e., roughly 8% of total vessels).[12] Therefore, ICF assumes that roughly 8% of total vessels contain refrigeration systems. UK MMO also provides historical UK fishing fleet size data from 1996-2009.

For merchant ships, data from the UK Department for Transport (UK DfT) (2011) were reviewed. Specifically, the UK DfT estimates that by the end of June 2011, there were 1,486 merchant ships (over 100 gigatonnes [GT]) registered on the UK Ship Register, with a total gross tonnage of 18,054,301. However, according to a representative of the UK Ship Register, only two of these merchant vessels were used to transport refrigerated cargo, and that they were used for world-wide commercial trade (Tong, 2011). Since these ships are used beyond domestic UK port-to-port transport, they are considered outside the scope for inclusion in the inventory.

Based on this information, ICF assumes that there were 527 marine transport refrigeration vessels in the UK in 2010 (which assumes that 8% of all vessels contain refrigeration systems). To estimate historical stock, ICF used UK MMO fishing fleet size data from 1996-2009, assuming that 8% of the fleet contains refrigeration systems; for earlier years (i.e., 1990-1995, for which no UK MMO data are available), ICF back-casted stocks using a trend function based on the derived 1996-2010 estimates.

Market Growth Rates

Oko-Recherche et al. (2011) estimate replacement growth for refrigerated vessels between 2007 and 2050 (i.e., constant fleet size with new sales replacing retired vessels). EC (2010) estimates annual growth of 2% until 2020, and 1% from 2021-2050. Entec (2010) references multiple sources that estimate annual growth of approximately 2.5% per year for general cargo vessels, between roughly 2% and 8% per year for container ships, and 0.5%-3% for all other ships. Based on the estimated stock data by type of ship, Entec's estimates would equate to a weighted average of approximately 3% per year.

Based on the above information, ICF conservatively assumes that the fleet of marine refrigerated transport vessels remains constant (i.e., replacement growth only) between 2010 and 2050, which is in line with the growth estimate for fishing-vessels provided by Oko-Recherche et al. (2011). The Oko-Recherche projections were chosen over the Entec estimates because they are specific to refrigerated vessels.

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[11] Merchant vessels, including general cargo ships and container ships, were considered for inclusion in this end-use; however, input from the UK Ship Register indicates that there were only two refrigerated merchant vessels registered in the UK in 2010 and that both of these vessels were used for worldwide commercial trade (Tong 2011). Since these vessels are used outside of the domestic (i.e., UK port-to-port) region, they were deemed outside the scope for inclusion in the inventory.

[12] All of the 527 vessels are assumed to weigh 100 gigatonnes (GT) or more, given that vessels 18-24 m in length average 129 GT, and those over 24 m in length average 500 GT (UK MMO 210).

Equipment Lifetime

Equipment lifetime estimates for marine transport refrigeration systems are available from Oko-Recherche et al. (2011), which assumes a 30-year lifetime for EU equipment; EPEE (2011), which assumes a 14-30 year lifetime for EU equipment; EC (2010), which estimates an average lifetime of 25 years for EU equipment; and (RTOC (2011), which estimates a lifetime range of 20-25 years worldwide. IPCC (2006) and IPCC (2000) estimate a range of 6-9 years for "transport refrigeration" equipment, but this estimate is not specific to marine transport. No default value is provided in IPCC (1996). Based on this information, ICF assumes an average lifetime of 25 years.

Refrigerant Use and Transitions

According to Honeywell, R-502 and, to a lesser extent, CFC-12, were historically used in marine transport refrigeration, which was displaced by HCFC-22 due to the CFC phaseout. R-404A entered the market in about 1995 and accounts for the lion's share of the current UK market (about 80%), with R-407C and ammonia accounting for the remainder. Retrofits have also been occurring in the UK to convert HCFC-22 equipment to HFCs, primarily R-417A. In future, R-407F will be adopted as an interim solution, with HFO blends (and to a lesser extent, ammonia) taking on a greater share of the market over the longer-term. Honeywell does not project CO_2 to be used in this application due to safety concerns. (Honeywell 2011b)

According to Oko-Recherche et al. (2011), refrigerated fishing vessels in the EU built before 2000 were charged with HCFC-22, while new systems built in 2000 or later use R-404A. The report also estimates that old systems will be converted from R-22 by the end of 2014, after which all smaller vessels (<70 meters in length) will use HFCs. From 2001 onwards, the authors estimate that nearly all new large ships (>70 meters in length) are equipped with natural refrigerants, such as ammonia (R-717) and CO2 (R-744).

Honeywell (2011a) projects that by 2030, R-404A will no longer be used in marine transport applications; rather, HFO blends and R-407F will dominate the market.

Based on this information, the tables below summarises the market penetrations of refrigerants into new/retrofit marine transport refrigeration vessels for key years. The percentages in the latter table represent the portion of original refrigerant remaining in eligible equipment (i.e., equipment with 20-70% of its useful life remaining) that is replaced by a retrofit refrigerant.

Table 86. Market Penetration of Refrigerants into Marine Transport Refrigeration*

Year	12	502	22	404A	407C	407F	717	HFO Blends
1990-1993	30%	60%	10%	-	-	-	-	-
1995	-	-	90%	10%	-	-	-	-
2001	-	-	-	99%	-	-	1%	-
2010	-	-	-	80%	10%	-	10%	-
2020	-	-	-	54%	-	30%	15%	1%
2030	-	-	-	-	-	15%	20%	65%
2050	-	-	-	-	-	-	30%	70%

* For years not listed, a linear change in market penetration between identified years is assumed.

Table 87. Market Penetrations of Retrofit Refrigerants into Existing Eligible Equipment*

Original	Retrofit	1990–1999	2000	2001	2009	2010	2014	2015	2016- 2050
12	22	-	100%	-	-	-	-	-	-
502	22	-	100%	-	-	-	-	-	-
22	417A	-	-	-	-	15%	10%	100%	-

* Eligible equipment for this end-use is defined as equipment with 20-70% of its useful life remaining. Figures are expressed as a percent of total metric tonnes of the remaining original refrigerant installed in existing eligible equipment. A linear change between identified years is assumed.

HFC Charge Size and Loss Rates

Charge Size

Equipment charge size estimates for marine transport refrigeration vary in the literature. Oko-Recherche et al. (2011) estimate a charge size range of less than 100 kg for small fishing trawlers to more than 8,000 kg in factory freezer fishing trawlers; but authors note that typical refrigeration charges range from 1,000 kg (for medium sized vessels 42-70 m in length) to 3,000 kg (for large fishing vessels >90 m). EC (2010) estimates an average charge size of 2,000 for HCFC-charged vessels and 1,500 for HFC-charged vessels. RTOC (2011) estimates a range of 10 to 500 kg for vessels >100 GT. IPCC (1996) provides an estimate of 8 kg for transport refrigeration sector, including trucks, trains and ships with refrigerated compartments; because this definition includes trucks and trains, the estimated charge size is likely to be an underestimate for marine transport refrigeration units. Similarly, IPCC (2006) and IPCC (2000) estimate a range of 3 - 8 kg for the full range of transport refrigeration equipment, including trucks, containers, reefers, and wagons—which is likely to be too low for ships alone. This information is summarised in the table below.

Table 88. Summary of Charge Size Estimates for Marine Transport Refrigeration

Source	Charge Size Estimate (kg)
EC (2010)	1,500 – 2,000
IPCC (2006)	3 – 8*
IPCC (2000)	3 – 8*
IPCC (1996)	8*
Oko-Recherche et al. (2011)	100 – 8, 000
RTOC (2010)	10 – 500

*IPCC estimates are for all types of transport refrigeration; they are not specific to ships.

Based on the above information, ICF assumes an average charge size of 1,500 kg for refrigerated vessels that are 100 GT and above. ICF assumes a higher charge size in the earlier years—2,000 kg in 1990 and 1,800 kg in 2000.

Manufacturing Loss

Neither IPCC (1996), IPCC (2000), nor IPCC (2006) provide default manufacturing loss rates specifically for marine transport. However, IPCC (1996) assumes an average of 2-5% for other stationary refrigeration and AC equipment, including transport refrigeration, and IPCC (2006) and IPCC (2000) assume a default loss rate range of 0.2-1% for “transport refrigeration.” Based on this information, ICF assumes a loss rate of 1%—consistent with the upper-bound estimate provided by IPCC (2000).

Operation Loss

IPCC (1996) estimates an average annual loss rate of 17% for other stationary refrigeration and AC equipment; while IPCC (2006) and IPCC (2000) estimate a range of 15-50% for transport refrigeration specifically. According to United Technologies (2011), an equipment manufacturer, marine containers leak at roughly 5% per year, but shipping vessels can leak up to 200% or more. Oko-Recherche et al. (2011) assume an annual leak rate of 40% for marine transport. Based on this information, ICF assumes a leak rate of 40% in 2010, which is in line with the EU-specific estimate developed by Oko-Recherche et al. and with IPCC (2006) and IPCC (2000). Furthermore, ICF assumes the average leak rate has decreased over time– starting at 50% in 1990—and reaching 30% by 2030, as technology and servicing practices improve. .

Disposal Loss

EC (2010) estimates a disposal loss rate of 3% for the EU-15, if a 100% compliance rate is assumed with recovery regulations (i.e., 60% of the original charge remains at disposal, of which 95% is technically recoverable). Oko-Recherche et al. (2011) estimate an average disposal loss rate of 30% in the EU. IPCC (1996) implies an average disposal loss rate of 18% for other stationary refrigeration and AC equipment, including transport refrigeration (assuming up to 90% of the original charge remains at equipment EOL and a recovery efficiency of 80%). IPCC (2006) implies a default disposal loss range for transport refrigeration equipment of 15% (assuming up to 50% of the original charge remains at equipment EOL and a recovery efficiency of 70%). IPCC (2000) estimates that 70-80% of the charge remaining at EOL is recoverable. This information is summarised in the table below.

Table 89. Summary of Available Disposal Loss Estimates for Marine Transport Refrigeration

Source	Percent of Original Charge Remaining at EOL	Recovery Efficiency (% of remaining charge that can be recovered)	Estimated Disposal Loss (as % of original charge)
EC (2010)	60%	95%	>3%
IPCC (1996)	90%	80%	≥18%
IPCC (2000)	NA	70-80%	≤20-30%
IPCC (2006)	50%	70%	≥15%
Oko-Recherche et al. (2011)	NA	NA	30%

Based on the above information, ICF assumes an average disposal loss rate of 30% from marine transport refrigeration vessels in 2010. This relatively high loss rate is consistent with the EU-specific estimate provided by Oko-Recherche et al. (2011) and is believed to be appropriate given how little is known about refrigerant-related activities/practices in the shipping sector, which may have lower rates of compliance with refrigerant recovery requirements given the lack of oversight. ICF assumes that this disposal loss rate decreases over time—starting at 50% in 1990 and reaching 20% by 2030—as recovery technology and technician practices improve.

Summary

The table below summarises the key assumptions for marine transport refrigeration.

Table 90. Summary of Key Assumptions for Marine Transport Refrigeration*

Input	1990	2000	2010	2020	2030-2050
Average HFC Charge Size (kg)	2,000	1,800	1,500	1,500	1,500
Manufacturing Loss Rate	1%	1%	1%	1%	1%
Operational Loss Rate	50%	45%	40%	35%	30%
Disposal Loss Rate	50%	35%	30%	25%	20%
Lifetime (years)	25				

*For years not listed, a linear change between identified years is assumed.

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4.12 Light Duty Mobile Air Conditioning

4.12.1 Overview of Previous Model Assumptions

The light duty mobile air conditioning end-use previously used a bottom-up approach to model HFC consumption and emissions. Stock estimates of passenger cars and vans were based on vehicle registration numbers provided by the Society of Motor Manufacturers and Traders (SMMT). HFC-134a was assumed to be the only HFC consumed in this end-use. R-134a first entered the market in 1993, growing to a total installed base of 1,544 MT in 2010. After 2016, no new mobile air conditioners were assumed to contain HFCs. In the previous model, equipment is assumed to have a lifetime of 12 years. Charge size and leak rate assumptions for select years are summarized in the table below.

Table 91. Previous Refrigerant Charge Size and Loss Rate Assumptions

Input	1990	2010	2050
Average HFC charge size (kg)	1.2	0.63	0.5
Manufacturing Loss Rate	1%	1%	1%
Lifetime Leak Rate	20%	8%	6%
Disposal Loss Rate	100%	10%	5%

4.12.2 End-Use Definition

Includes AC systems for passenger cars and light commercial vehicles (up to 3.5 tonnes). Both of these vehicle types are covered under Directive 2006/40/EC (the MAC Directive).

4.12.3 Summary of Research Findings and Updates

Equipment Stocks and Growth Rate

Stocks

The stock of passenger car and light commercial mobile air-conditioning (MAC) systems in the UK can be estimated based on stock data from SMMT (2011) and assumptions on AC penetration rates from Gluckman (2011). Specifically, SMMT provides data on the total of cars and light commercial vehicles on UK roads from 2000 to 2010 (e.g., 31,258,197 cars and 3,566,460 light commercial vehicles in 2010). UK DECC (2011) estimates that 5% of new cars sold in 1990 were equipped with AC systems, increasing to reach 80% of new cars sold in 2008. Using these AC market penetration estimates, the SMMT data on number of cars can be used to estimate total number of passenger MAC units from 2000 to 2010. In addition, based on anecdotal information from industry experts, it is assumed that roughly 80% of newly manufactured light duty MACs are imported pre-charged into the UK.

Market Growth Rates

Ideally, the MAC fleet should be grown based on the auto sector growth estimates used by DECC to project CO_2 emissions for the UK. However, as these growth rates were not made available by the UK Department for Transport in time for the model completion, ICF calculated historical growth rates based on the growth in estimated number of MAC units for passenger and light commercial vehicles from 2000-2010 (which equates to roughly 6.9% per year when factoring in growth in vehicles and AC penetration). From 2010-2015, ICF assumes an average annual growth rate based on SMMT (2011) data on cars and light commercial vehicles in use from 2000 to 2010 (which equates to roughly 1.3% growth per year). From 2016-2030, ICF conservatively decreased the rate to 1.0%, and assumes zero growth from 2030-2050. For earlier years (i.e., 1990-1999) ICF back-casted stocks using an average annual growth rate derived from SMMT (2011) data for 2000-2010.

Equipment Lifetime

Oko-Recherche et al. (2011) and EPA (2006) estimate that the lifetime of passenger car MAC systems is 12 years, while EC (2010) estimates an average lifetime of 14 years. IPCC (1996) and IPCC (2000) estimate an average equipment lifetime of 12 years for MAC, while IPCC (2006) estimates a lifetime of 9-16 years.

Based on the 2010 fleet size and new registrations data provided by SMMT (2011),[13] the implied equipment lifetime (assuming no market growth) is at least 15 years. Based on this information, ICF assumes an equipment lifetime of 15 years.

Refrigerant Use and Transitions

According to RTOC (2010), CFC-12 was historically used in passenger MAC systems. One industry representative indicated that 100% of the MAC market still used CFC-12 in 1992 (Gluckman 2011). CFC-12 systems were retrofitted primarily with HFC-134a, although some systems in the North America and Australia were directly transitioned from CFC-12 to HCs. AEA (2010) similarly estimates that CFC-12 was commonly used until 1993, when it was replaced by HFC-134a as the new standard.

As a result of the MAC Directive, HFC-134a must be replaced by low-GWP alternatives in new model vehicles beginning in 2011. According to RTOC (2010), HFO-1234yf qualifies for use in the EU. In addition to HFO-1234yf, CO_2, HFC-152a, and other blend alternatives may also displace R-134a in the future (TEAP 2010).

Oko-Recherche et al. (2011) assume that by 2012, HFO-1234yf will account for 15% of the new market, reaching 75% in 2016, and 96% from 2017 through 2050; the remaining 4% of the market beyond 2017 is presumably CO_2.

One major refrigerant producer reported that HFO-1234yf has been selected by MAC manufacturers globally as the alternative to HFC-134a in passenger MACs, at least in the near-term; however, to-date it only represents a very small share of the European market (i.e., less than 5%). By 2015-1016, use of HFO-1234yf is expected to significantly ramp up, once OEMs have had one or two years of experience to test and refine the technology. (Honeywell 2011)

Based on the above information, ICF assumes the market penetrations of refrigerants in new light duty MACs sold in the UK for key years, as shown in the table below. The percentages in the latter table represent the portion of original refrigerant remaining in eligible equipment (i.e., equipment with 25-75% of its useful life remaining) that is replaced by a retrofit refrigerant.

Table 92. Revised Market Penetration of Refrigerants into New Light Duty MACs*

Year	12	134a	1234yf
1990-1992	100%	-	-
1993	50%	50%	-
1994	-	100%	-
2010	-	100%	-
2011	-	98%	2%
2015	-	60%	40%
2020-2050	-	-	100%

* For years not listed, a linear change in market penetration between identified years is assumed.

Table 93. Revised Market Penetrations of Retrofit Refrigerants into Existing Eligible Equipment*

Original	Retrofit	1990–1999	2000	2001- 2050
12	134a	-	25%	-

* Eligible equipment for this end-use is defined as equipment with 25-75% of its useful life remaining. Figures are expressed as a percent of total metric tonnes of the remaining original refrigerant installed in existing eligible equipment. A linear change between identified years is assumed.

[13] Fleet size (~31.26 million) divided by the number of new registrations (~2.03 million) suggests an approximate average lifetime of 15.4 years. While this calculation does not account for fleet growth, the UK automobile fleet size is believed to be fairly mature (i.e. only growing slowly); however, to the extent that some of the 2.03 million new registrations are for fleet growth and not replacement, the suggested average lifetime would be even greater than that calculated here.

HFC Charge Size and Loss Rates

Charge Size

RTOC (2011) estimates an average charge size range of 0.4 to 1.2 kg for passenger car MAC. Oko-Recherche et al. (2011) estimate an average charge size for passenger MACs in the EU of 0.67 kg in 2010, decreasing to 0.63 kg by 2015; and EC (2010) estimates an average charge of 0.7 kg for the EU-15. However, comments received on the draft EC (2010) report from EFCTC support the assumption by Oko-Recherche et al. that average charge size will decrease in the near future; specifically, EFTC maintained that, while the average charge size of an EU passenger MAC system in 2010 may be about 700 g, the size is expected to be significantly below 750 g by 2015—perhaps 15% lower (640 g). Oko-Recherche et al. (2011) also estimate an average charge size of 0.9-1.2 kg for light commercial vehicles (depending on vehicle type).

IPCC (1996) estimates the typical refrigerant charge for MACs at 1.2 kg for cars and 1.5 kg for trucks, noting that MACs in newer cars may have a lower charge (e.g., 800 g). IPCC (2000) provides a default average charge size of 0.8 kg, while IPCC (2006) estimates a charge size range of 0.5 to 1.5 kg for all types of MACs. This information is summarised in the table below.

Table 94. Summary of Charge Size Estimates for Light Duty MACs

Source	Charge Size Estimate (kg)
EC (2010)	0.7
EFCTC (2010)	0.70 (passenger, 2010) 0.64 (passenger, 2015)
IPCC (1996)	0.8 (new passenger) 1.2 (old passenger) 1.5 (light commercial)
IPCC (2000)	0.8
IPCC (2006)	0.5 – 1.5
Oko-Recherche et al. (2011)	0.67; 0.63 in 2015 (passenger) 0.9- 1.2 (light commercial)
RTOC (2010)	0.4 – 1.2

Based on these estimates, ICF assumes an average charge size of 0.73 kg in 2010 for passenger and light duty vehicles, decreasing to 0.67 kg by 2015. ICF assumes that the average charge size has decreased from 1990 to present (i.e., from 0.85 kg in 1990 and 0.80 kg in 2000) due to technology improvements over time.

Manufacturing Loss

The IPCC (1996) default manufacturing loss range for MACs is 4-5%, while IPCC (2006) estimates a range of 0.2-0.5%. IPCC (2000) estimates a default manufacturing emissions rate of 0.5%. Based on the IPCC (2000) estimate, ICF assumes a leak rate of 0.5%.

Operation Loss

Oko-Recherche et al. (2011) estimate a lifetime leak rate of 10% for MAC systems, which is in line with the IPCC (2006) and IPCC (2000) default estimate of 10-20%. IPCC (1996) estimates an annual leak rate of 30% for MACs. AEA (2010) estimates that the leak rate of new MAC systems is likely to be around 6-8% per year, with the potential to decrease to about of 4-5% or even lower in future.

One industry representative indicated that an average operation loss rate of 10% in 2010 was reasonable and that the rate could drop to as low as 8% in the future; an overall decrease below 8% is unlikely in future, however, due to vehicle accidents that damage MAC equipment (Gluckman 2011).

Based on this information, ICF assumes that operation loss rates have decreased from the high end of the IPCC range in 1990 (i.e., 20%, as currently assumed in the model) to the low end of the range in 2010 (i.e., 10%), and then assumes that the leak rate will decrease slightly further, reaching 8% by 2030 due to improved refrigerant recovery practices and technology design.

Disposal Loss

Oko-Recherche et al. (2011) estimate a disposal loss rate of 30%. EC (2010) estimates that 60% of refrigerant charge remains at end-of-life, with 90% of that amount being technically recoverable—implying a loss rate of only 6%, assuming full compliance with refrigerant recovery requirements. EPEE (2011) estimates a 2006 recovery efficiency of 0% from passenger MACs, with a potential recovery potential of 40%—implying that compliance with recovery requirements at vehicle EOL was non-existent across the EU in 2006. Anecdotal information across the EU further supports the belief that compliance with recovery requirements in this sector is low, given that oversight is difficult and Regulation (EC) No 842/2006 is ambiguous about whether EOL recovery from MACs is even required; specifically, MAC systems are covered by Article 4.3 of the Regulation, which states that recovery only needs to be done "if technically feasible and does not entail excessive cost" (Caleb and SKM Enviros 2011).

IPCC (1996) implies a disposal loss rate of 15% (assuming up to 75% of initial charge remains at equipment EOL and a recovery efficiency of 80%), while IPCC (2006) implies a disposal loss rate of 25% (assuming up to 50% of initial charge remains at equipment EOL and a recovery efficiency of 50%). IPCC (2000) assumes that 40% of the charge remains at EOL and 0% is recovered.
This information is summarised in the table below.

Table 95. Summary of Available Disposal Loss Estimates for Light Duty MACs

Source	Percent of Original Charge Remaining at EOL	Recovery Efficiency (% of remaining charge that can be recovered)	Estimated Disposal Loss (as % of original charge)
Oko-Recherche et al. (2011)	NA	NA	30%
EC (2010)	60%	90%	>6%
IPCC (1996)	75%	80%	≥15%
IPCC (2000)	40%	0%	40%
IPCC (2006)	50%	50%	≥25%

Based on these estimates, ICF assumes a disposal loss rate of 30% in 2010, in line with the EU specific estimate from Oko-Recherche. ICF also assumes that the disposal loss rate decreased from 1990 to present (i.e., 50% in 1990 and 40% in 2000) in response to refrigerant recovery regulations, as well as improved refrigerant recovery practices and technologies. By 2030, ICF assumes that the disposal loss rate will decline further to reach 20%. Additional research is needed to determine whether disposed vehicles are often exported for resale outside of the UK, which could lead to an over-estimation of disposal losses in the model.

Summary

The table below summarises the revised assumptions related to HFC charge size and loss rates.

Table 96. Summary of Revised Charge Size and Loss Rate Assumptions for Light Duty MACs*

Input	1990	2000	2010	2020	2030-2050
Average HFC Charge Size (kg)	0.85	0.80	0.73	0.67	0.67
Manufacturing Loss Rate**	0.5%	0.5%	0.5%	0.5%	0.5%
Operational Loss Rate	20%	15%	10%	10%	8%
Disposal Loss Rate	50%	40%	30%	25%	20%

*For years not listed, a linear change between identified years is assumed.
** 80% of units assumed to be manufactured pre-charged outside UK, based on anecdotal information from industry experts.

4.12.4 Summary of Model Updates

The table below summarises the model updates described above for an indicative list of parameters, based on the research conducted.

Table 97. Comparison of Previous vs. Revised Assumptions for Key Parameters

Input	Previous	Revised
Average HFC charge size (kg) for equipment built in 2010	0.63	0.73
Manufacturing Loss Rate (2010)	1%	0.5%
Operational Loss Rate (2010)	8%	10%

Disposal Loss Rate (2010)	10%	30%
Lifetime (years)	12	15

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4.13 Other Mobile Air Conditioning

4.13.1 Overview of Previous Model Assumptions

No end-use previously existed in the model to account for non-passenger vehicle types of mobile air conditioning.

4.13.2 End-Use Definition

AC systems for trucks (over 3.5 tonnes), buses/coaches, semi-trailers, trailers, and railcars.[14]

4.13.3 Summary of Research Findings and Updates

Equipment Stocks and Growth Rate

Stock Data

The stock of other vehicles likely to contain MACs can be estimated based on data from SMMT (2011) for trucks and buses/coaches; and Eurostat (2011) for semi-trailers, trailers, and railcars. Specifically, SMMT provides the number of trucks and buses/coaches in-use on UK roads each year from 2000 to 2010. Eurostat (2011) provides data on the number of semi-trailers, trailers, and railcars by EU Member State from 1998 to 2009. UK-specific data is not provided across the time series for these vehicle types; therefore, ICF calculated an average ratio between the stock for each vehicle type and GDP for France, Italy, and Spain, and applied this average ratio for each vehicle type to UK's GDP to estimate stock for each type of vehicle. Assumptions on AC penetration rates within these types of vehicles can be obtained from Oko-Recherche et al. (2011), which estimates that MAC penetration rates in East Europe/UK in 2010 were 57% for buses, 35% for medium trucks, and 87% for large trucks. ICF used these AC penetration rates as proxies for penetration rates in all other vehicle types, namely: medium trucks as a proxy for trucks and semi-trailers; large trucks as a proxy for trailers; and buses as a proxy for railcars

Based on the above data sources, ICF assumes the following number of Other MAC units installed in the UK in 2010.

Table 98. Estimated Number of Other MACs in the UK by Vehicle Type (2010)

Vehicle Type[a]	Stock Estimate	AC Penetration Rate	Total Units	Percentage of Total
Trucks	563,295	35%	197,153	39%
Buses/Coaches	90,700	57%	51,699	10%
Semi-Trailers	349,275	35%	122,246	24%
Trailers	145,975	87%	126,998	25%
Railcars	1,879	57%	1,071	0.2%
TOTAL	**1,107,452**		**499,168**	

[a] Data for Trucks, and Buses/Coaches from SMMT (2011); data for Semi-Trailers, Trailers, and Railcars based on Eurostat (2011).

Market Growth Rates

Ideally, the heavy duty MAC fleet should be grown based on the auto sector growth estimates used by DECC to project CO_2 emissions for the UK. However, as these growth rates were not made available by the UK Department for Transport in time for the model completion, ICF calculated historical growth rates based on the growth in estimated number of MAC units for these vehicle types (i.e., trucks, buses/coaches, trailers,

[14] AC systems in ships and agricultural equipment (i.e., road tractors) were considered for inclusion in this definition, but ultimately were determined to be out of scope for inventory quantification as neither IPCC (1996) nor IPCC (2006) include these vehicle types in their definitions for "mobile AC." Should these vehicle types be added to the Other Mobile AC end-use in future, data from Eurostat (2011) and Oko-Recherche et al. (2011) could be used to calculate stock estimates for road tractors and ships, respectively.

semi-trailers, and railcars) from 2000-2010 (which equates to roughly -1.7% per year). To project future growth, ICF assumes the same annual growth rates as the Light Duty MAC end-use (i.e., 1.3% growth per year from 2010-2015, 1% per year from 2016-2030, and 0% per year from 2030-2050).

Equipment Lifetime

Oko-Recherche et al. (2011) estimate an MAC lifetime of 10 years for trucks and buses and 25 years for railcars. IPCC (1996) and IPCC (2000) assume an average equipment lifetime of 12 years for MAC equipment, while IPCC (2006) estimates 9-16 years. Based on each vehicle type's percentage of the total fleet and using Oko-Recherche et al.'s lifetime assumptions by vehicle type, ICF assumes a weighted average lifetime of 10 years.

Refrigerant Use and Transitions

Refrigerant transitions were estimated based on the following information:

- Oko-Recherche et al. (2011)
  - Rail: prior to 1995, R-12 was primarily used in Northern Europe. Since 2000, only HFCs are used in new systems and are being applied for conversions as well (typically R-134a). For simplicity, authors assume R-134a only.
  - Trucks/Buses: No data.
- EC (2008)
  -
  - Rail stock in-use in 2008: 75% R-134a, 25% R-407C
  - Trucks/trailers stock in-use in 2008: 93% R-404A, 2% R-410A, 5% R-134a
- EC (2010)
  - Buses: in 2010: EU-15 bank included 2% CFC-12, 98% R-134a; by 2020, 95% R-134a and 5% low-GWP alternatives
- RTOC (2010)
  - Bus/Rail: 50% of fleet worldwide uses R-22, the rest use mostly R-134a or R-407C
- TEAP (2010)
  - Trucks/Buses: those built before mid-1990s used CFC-12; new vehicles use R-134a.
- Honeywell (2011a, 2011b)
  - R&D efforts are currently underway to test the use of HFO-1234yf in truck/bus MAC systems. This refrigerant is already being used in a small share of new passenger MACs across Europe and use is expected to ramp up significantly in 2015/2016, after original equipment manufacturers (OEMs) have a few years of experience to test and refine the technology. With additional R&D and field experience, it is reasonable to assume that HFO-1234yf will be adopted in other types of vehicle AC by 2020 (2011b).
  - R-407C is used in approximately 25% of new other MAC equipment today (2011a).
- Gluckman (2011)
  - Larger MACs (i.e., trains) may use R-407C or R-410A.

Based on the above information, ICF assumes the following market penetrations for the various vehicle types:

- **Buses/Trucks/Trailers**: transitioned from R-12 to R-22 by 1993; began transition to R-134a in mid-1990s, with transition complete by 2001; future EC Directive likely to apply MAC Directive to buses/trucks and OEMs already investing R&D into alternatives, so assume transition to alternatives (e.g., HFO-1234yf, CO_2) begins in 2020.
- **Rail:** 100% R-12 used until 1993, when transitioned to HFCs (primarily HFC-134a and some R-407C or R-410A) began and linearly reached 100% by 1995. Transition away from HFCs will begin in 2030 and go to HFO-1234yf to reach 50% by 2050.

Based on each vehicle type's percentage of the total stock, ICF assumes the market penetrations of refrigerants in new other MACs sold in the UK for key years, as shown in the table below.

Table 99. Market Penetration of Refrigerants into New Other MACs*

Year	12	22	134a	407C	1234yf	744
1990	98%	2%	-	-	-	-
1993	-	85%	15%	-	-	-
2001	-	-	100%	-	-	-
2010	-	-	75%	25%	-	-
2015	-	-	75%	25%	-	-
2020	-	-	40%	10%	45%	5%
2030-2050	-	-	-		90%	10%

* For years not listed, a linear change in market penetration between identified years is assumed

HFC Charge Size and Loss Rates

Charge Size

Oko-Recherche et al. (2011) estimate an average charge size of 0.9-1.2 kg for trucks (depending on type), 11 kg for buses (in 2010), and 8 kg for railcars. EC (2008) estimates a charge size of 5 kg for trucks, 9 kg for trailers, and 5-30 kg for railcars. IPCC (1996) estimates an average charge size for trucks of 1.5 kg, while IPCC (2000) provides a default average charge size of 0.8 kg and IPCC (2006) estimates a range of 0.5-1.5 kg for all types of MACs. This information is summarised in the table below.

Table 100. Summary of Charge Size Estimates for Non-Passenger MACs

Source	Charge Size Estimate (kg)
EC (2010)	5 (trucks) 9 (trailers) 5 – 30 (railcars)
IPCC (1996)	1.5
IPCC (2000)	0.8
IPCC (2006)	0.5 – 1.5
Oko-Recherche et al. (2011)	0.9 – 1.2 (trucks) 11 (buses) 8 (railcars)

Based on these assumptions and each vehicle type's percentage of total stock, ICF assumes an average charge size of 4 kg in 2010, decreased from 5 kg in 1990 due to technology improvements. This is outside of the range set out in the IPCC guidelines (1996, 2000 and 2006), but is consistent with the most recent EU-specific estimates set out in Oko-Recherche et al. (2011).

Manufacturing Loss

The IPCC (1996) default manufacturing loss range for MACs is 4-5%, while IPCC (2006) estimates a range of 0.2-0.5%. IPCC (2000) estimates a default manufacturing emissions rate of 0.5%. Based on the IPCC (2000) estimate, ICF assumes a loss rate of 0.5%.

Operation Loss

Operation loss rate will be estimated based on Oko-Recherche et al. (2011), who estimate a rate of 10-15% for trucks, 15% for buses, and 7% for railcars. EC (2008) presents similar estimates, 5-10% for trucks and trailers, 10% for buses built after 2000 and 20% for buses built pre-2000. IPCC (1996) estimates an annual leak rate of 30% for MACs, while IPCC (2006) and IPCC (2000) provide a default range of 10-20%. Based on each vehicle type's percentage of total stock, ICF assumes a weighted average operation loss rate of approximately 10%.[15] Furthermore, ICF assumes that this loss rate has decreased significantly from 1990-present (i.e., 20% in 1990) and will continue to decrease by 2030 (i.e., reaching 5%).

Disposal Loss

Oko-Recherche et al. (2011) estimate a disposal loss rate of 70% for trucks and buses, and 30% for railcars. EPEE (2011) assumes 0% recovery efficiency in 2006 across the EU for buses and trailers, and 40% for

[15] This assumes an average loss rate of 10% for trucks, 12.5% for buses, and 7% for railcars.

trains. EC (2010) estimates that these equipment types have 60-70% of refrigerant charge remaining at time of disposal, with 90-95% of that charge being technically recoverable—i.e., loss rate of 3-7%, assuming full compliance with refrigerant recovery requirements. IPCC (1996) implies a disposal loss rate of 15% for MACs (assuming up to 75% of initial charge remains at equipment EOL and 80% recovery); while IPCC (2006) implies a rate of 25% (assuming up to 50% of initial charge remains at equipment EOL and 50% recovery). IPCC (2000) assumes that 40% of the charge remains at EOL and 0% is recovered. This information is summarised in the table below.

Table 101. Summary of Available Disposal Loss Estimates for Non-Passenger MACs

Source	Percent of Original Charge Remaining at EOL	Recovery Efficiency (% of remaining charge that can be recovered)	Estimated Disposal Loss (as % of original charge)
EC (2010)	60-70%	90-95%	>3-7%
IPCC (1996)	75%	80%	≥15%
IPCC (2000)	40%	0%	40%
IPCC (2006)	50%	50%	≥25%
Oko-Recherche et al. (2011)	NA	NA	30% (railcars) 70% (trucks)

Based on these estimates, ICF assumes a disposal loss rate of 30% in 2010. This loss rate is lower than that estimated by IPCC (2000) but in line with the EU-specific estimates provided by Oko-Recherche (2011). ICF assumes that the disposal loss rate has decreased significantly from 1990 to present (i.e., 50% in 1990 and 40% in 2000) due to more common/ improved recovery and technologies, and that the disposal loss rate will decrease further by 2030 (i.e., reaching 20%). Additional research is needed to determine whether disposed vehicles are often exported for resale outside of the UK, which could lead to an over-estimation of disposal losses in the model.

Summary

The table below summarises the revised assumptions related to HFC charge size and loss rates.

Table 102. Summary of Charge Size and Loss Rate Assumptions for Other MACs*

Input	1990	2000	2010	2020	2030-2050
Average HFC Charge Size (kg)	5	5	4	4	4
Manufacturing Loss Rate	0.5%	0.5%	0.5%	0.5%	0.5%
Operational Loss Rate	20%	15%	10%	8%	5%
Disposal Loss Rate	50%	40%	30%	25%	20%
Lifetime (years)	10				

*For years not listed, a linear change between identified years is assumed.

4.13.4 References

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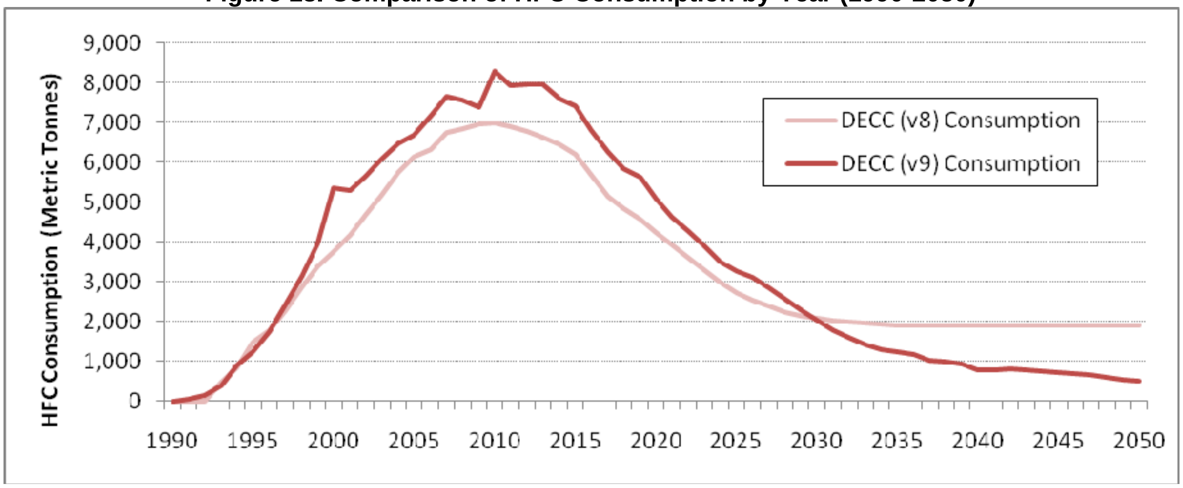
5 Comparison to Previous Model

A comparison of estimated annual HFC consumption (i.e., the amount used to manufacture new equipment produced in the UK plus the amount used to service leaking equipment) generated by the previous version of the DECC model (v8) and the revised version of the DECC model (v9) is presented below in Figure 18. Similarly, a comparison of estimated annual HFC emissions (i.e., manufacturing emissions plus operational emissions plus disposal emissions) generated by both models is presented in Figure 19. As shown HFC consumption estimated closely align, with historical consumption estimates in the revised model (v9) closely mirroring those in the previous model (v8) through the 1990s, but slightly higher from about 2000 to 2025 and lower beyond 2030. The revised model's higher consumption estimates in recent years is consistent with other top-down data (see Section 6), and corrects for the previous model's underestimates that were noted in AEA (2011).[16] The reduced consumption beyond 2025 is the result of the new model's improved projections of the transition away from HFCs.

Figure 18. Comparison of HFC Consumption by Year (1990-2050)



Estimated HFC emissions generated from the revised version of the model (v9) are significantly greater than the emissions estimated by the previous model (v8), and also align with observed emissions data (see Section 6). The discrepancy between the two versions of the models is largely due to the difference in disposal emissions assumptions, which are assumed to be greater in the revised model, and to the revised definitions/further disaggregation of end-uses—including marine transport, other MACs, and building AC.

Figure 19. Comparison of HFC Emissions by Year (1990-2050)

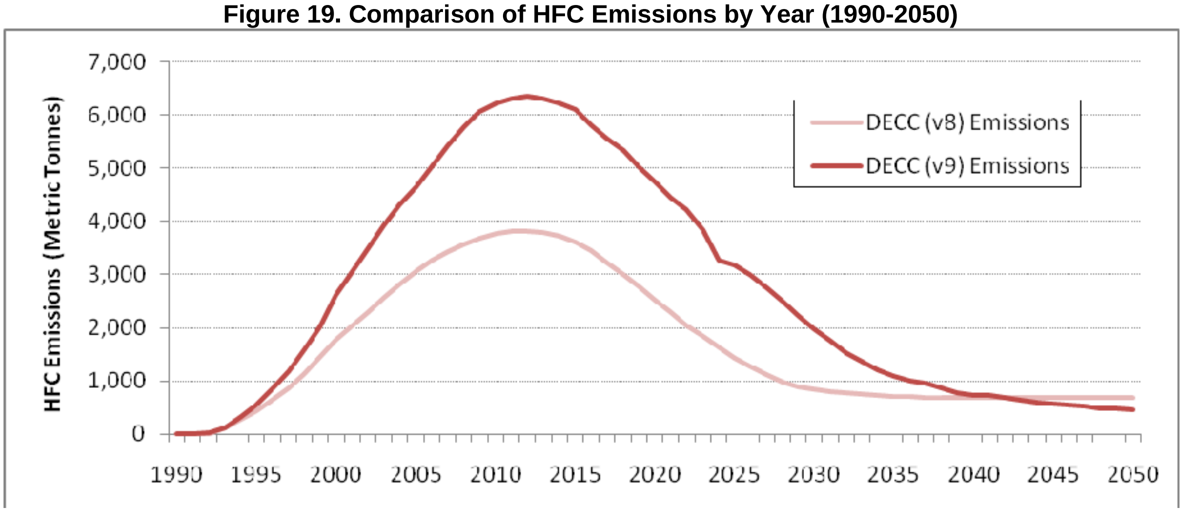


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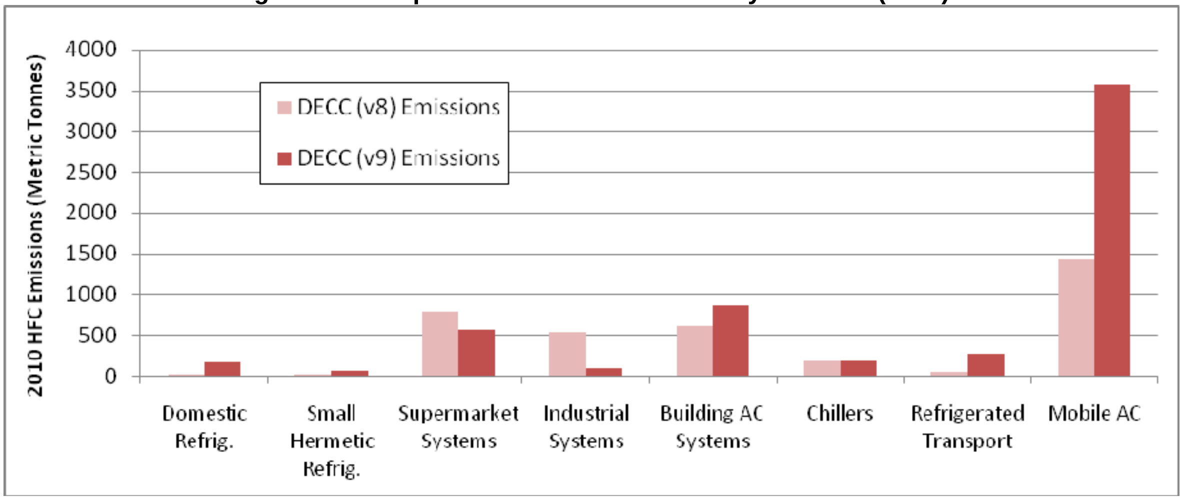
Figure 20. Comparison of HFC Emissions by End-Use (2010)



6 Model Validation

To validate the bottom-up model described in this report, comparisons to top-down refrigerant sales data and emission observations were performed, as presented below.

6.1 Comparison to Top-Down Data

To validate the bottom-up model described in this report, a comparison to top-down refrigerant sales data was performed using data by the British Refrigeration Association (BRA), which contains a comprehensive set of UK HFC sales. Specifically, the BRA report estimates UK sales of HFC refrigerants by surveying the industry. The response rate for all sectors in this report is generally high with all key refrigerant Producers and Fillers & Packers reporting. All the principal wholesalers also reported, together with a significant number of other important merchants in 2007 and 2008. The BRA report is considered to be the only report that contains data on HFC sales in the UK.[17]

ICF compared UK virgin refrigerant sales volumes reported by HFC producers in metric tonnes available from BRA (2011)[18] to the quantity of HFC refrigerant estimated in the revised DECC (v9) model that is (1) used to manufacture new equipment produced in the UK and (2) used to service leaking equipment. The BRA sales data cannot be reproduced here as they are commercially confidential; however, sales of HFCs have increased gradually between 2006 and 2010 with a small reduction in sales in 2008.

The results of the comparison reveal that the data sets align closely, with the revised DECC (v9) output showing the same trends and totalling only about 5% above the collective annual BRA data for HFCs from 2006-2010. The discrepancy between DECC (v9) and BRA data for ODS consumption is significantly larger (42%), but this is expected given that the model inputs were not tailored to ODS refrigerants (e.g., ODS charge sizes and leak rates are typically higher than for HFCs, which is not accounted for in the model, but would lead to higher ODS consumption estimates).

When comparing refrigerant use by refrigerant type (HFC-134a, R-404A/507, R-407C, R-410A, Other HFCs), the results of the revised DECC model again are aligned with the BRA production data. Future efforts on improving reconciliation between estimated usage and the BRA data for particular fluids should focus on HFC-134a (which the DECC model estimates to be about 35% higher than BRA) and R-404A (which the DECC model estimates to be about 33% lower than BRA). Efforts were made to better align the model's consumption of these two refrigerants with the BRA data, while still accounting for the industry-specific input gathered for this study. This discrepancy is discussed further in Section 8 (Future Model Updates). The model results are believed to be reasonable given the diverse reasons why these data sets do not directly align. In particular:

1. Annual equipment leakage is not necessarily refilled each year, which could cause BRA data to be higher or lower in any given year; over time. However, one would expect the trend in refrigerant use for servicing to balance out between both data sets.
2. Refrigerant purchases in the after-market sector could be stockpiled for future use, which would cause BRA data to be higher; again, one would expect any spikes in stockpiling to smooth out over time, but it is especially uncertain for HCFCs, in light of the current phaseout.
3. Quantities of refrigerant recovered for reuse are not captured in the BRA dataset,[19] which would cause the BRA data to be lower. The reuse of refrigerant is probably greatest in the large commercial and industry refrigeration sectors.

[17] At this time, the only official reporting requirement for companies is under the F-gas regulations. Article 6 of Regulations (EC) No 842/2006 on certain fluorinated greenhouse gases requires companies that produce, import, or exports more than one metric tonne of fluorinated GHG report certain activities to the European Commission annually, beginning of 2008. The data provides information on the volume of HFCs imported and exported at the EU level by species, however the data is not disaggregated into the quantities going in and out of each Member State. There are no other reporting requirements for companies to report their HFC usage/sales within the UK.

[18] These data represent the sales of refrigerant solely into the UK at the top of the UK Distribution Chain—i.e., used to manufacture new equipment and service the after-market. Data were available for CFCs, HCFC-22, HCFC blends, HFC-134a, R-404a/507, R-407C, R-410A, and other HFCs.

[19] BRA data includes some information on quantities of refrigerant returned for reclamation and subsequent resale for certain years (between 2007 and 2010) and refrigerant types (HCFC-22), but because this dataset is incomplete, these data are not included in the comparison figures above.

6.2 Comparison to Emission Observations

In order to provide some verification of the UK Greenhouse Gas Inventory (GHGI), DECC has established and maintained a high-quality observation station at Mace Head on the west coast of Ireland since 1986. The station reports high-frequency concentrations of the key greenhouse gases and is under the supervision of Dr. Simon O'Doherty of the University of Bristol (O'Doherty et al. 2004).[20]

The Met Office, under contract to DECC, employs the Lagrangian dispersion model NAME (Numerical Atmospheric dispersion Modelling Environment) (Ryall et al. 1998)[21] (Jones et al. 2007)[22] driven by 3D synoptic meteorology from the ECMWF (ERA-Interim) (1995-2002) and the Met Offices' numerical weather prediction model (2003-2009) to generate so called air-history maps. The air-history maps represent the recent 12-day history of the air before it arrives at the observing station, Mace Head, and estimate the dilution in concentration that surface sources would undergo during this transport. These maps have been generated for each 3-hour period from 1995 to current day and enable the observations made at Mace Head to be sorted into those that represent Northern Hemisphere baseline air masses and those that represent regionally-polluted air masses arriving from Europe. From the sorted data an estimate of the time-varying Northern Hemisphere mid-latitude baseline concentration is made.

The Mace Head observations, with the baseline removed, and the 3-hourly air-history maps are applied in an inversion algorithm to estimate the magnitude and spatial distribution of the European emissions that best support the observations (Manning et al. 2003).[23] The technique has been applied to HFC-134a, in addition to other HFCs (HFC-152a), methane, and nitrous oxide.

The inversion (best-fit) technique, simulated annealing, is used to fit the model emissions to the observations. It assumes that the emissions from each grid box are uniform in both time and space over the duration of the fitting period. This implies that the release is independent of meteorological factors such as temperature and diurnal cycles, and that in its production and use there are no definite cycles or intermittency. The geographical area defined as UK within the NAME estimates includes the coastal waters around the UK. A 'best fit' solution has been determined for each three-year period (Jan '95-Dec '97, Feb '95-Jan '98… Dec '06-Nov '09). The uncertainty ranges have been estimated by solving each 3-year period multiple times (26) with a random noise perturbation (based on the standard of the points classed as baseline) applied to the observations. The annual estimates have been calculated by taking the median of the solutions with the full year represented in the solution period.

Comparisons of the NAME and GHGI (DECC model v8) estimates are presented below to the revised DECC model (v9) emission estimates for HFC-134a. As shown, the DECC v9 model HFC-134a emission estimates align more closely with the observed emissions than the previous version of the model (v8).

Table 103. Verification of the UK emission inventory estimates for HFC-134a in Gg yr^{-1} for 1995-2008

Source	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
NAME	1.3	1.2	1.2	1.1	1.3	1.8	1.8	2.0	2.3	2.3	2.3	2.4	2.4	2.3
GHGI	0.7	1.2	1.8	2.4	2.4	2.7	3.0	3.3	3.7	3.9	4.3	4.3	4.5	4.5
DECC Model (v9)	0.5	0.8	1.0	1.3	1.6	2.0	2.3	2.6	2.8	3.0	3.2	3.4	3.6	3.9

Source: AEA. (2011). "UK Greenhouse Gas Inventory, 1990 to 2008: Annexes." April 2010. ISBN 0-9554823-9-9. Available at: http://uk-air.defra.gov.uk/reports/cat07/1010151420_ukghgi-90-08_Annexes_Issue3_r.pdf.

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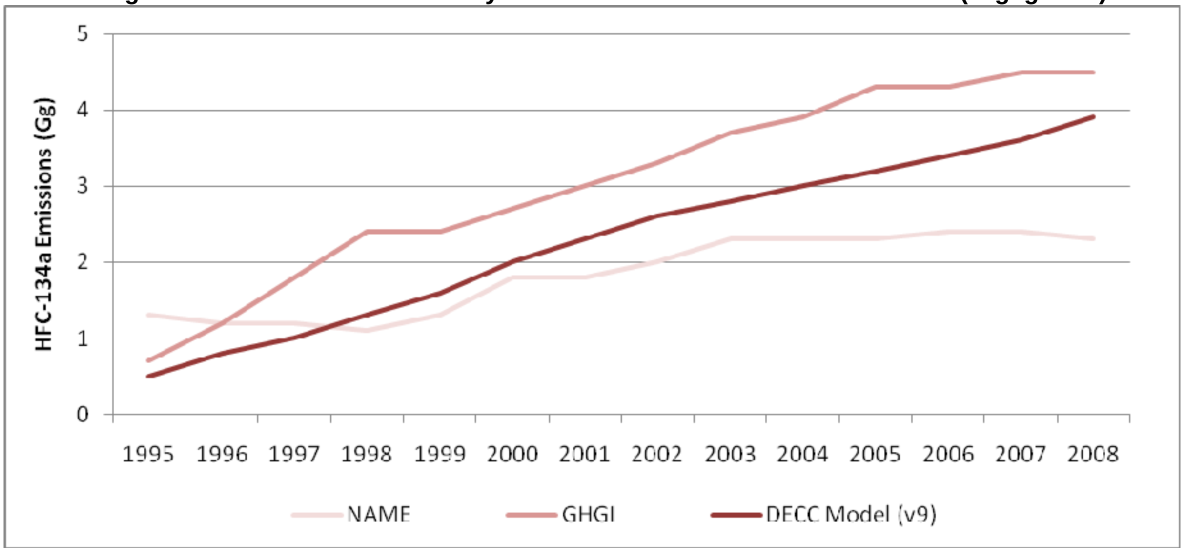
Figure 21. UK emission inventory estimates for HFC-134a for 1995-2008 (Gigagrams)



7 Uncertainty Analysis

The Tier 2 bottom-up analytical modelling approach used to estimate emissions from refrigeration/air conditioning equipment is IPCC compliant. Although the DECC model is more comprehensive than the IPCC default methodology, significant uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

In order to calculate uncertainty, functional forms were developed to simplify some of the complex aspects of the refrigeration and air-conditioning sector. In particular, because emissions are calculated based on the entire lifetime of equipment, not just equipment put into commission in the current year, simplifying equations were used. The functional forms used variables that included growth rates, lifetimes, emission factors (manufacturing, operational, and disposal emission rates), refrigerant transitions, charge size, disposal quantities, and new and existing stock. Uncertainty was estimated around each variable within the functional forms based on ICF's expert judgment, taking into account the range of estimates provided in the literature and by industry stakeholders. A Monte Carlo simulation analysis was performed and uncertainty bounds were generated using 10,000 simulations. The most significant sources of uncertainty for this source category include the emission factors for centralised supermarket refrigeration systems and marine transport refrigeration—two end uses with significant installed base (due to large stock and/or charge size).

The results of the Tier 2 quantitative uncertainty analyses for 1995 (base year) and 2010 are summarised in Table 104.[24] For 1995, HFC emissions were estimated to be between 723.4 and 808.4 gigagrams of carbon dioxide equivalent (Gg CO_2 Eq.) at the 95% confidence level; this indicates a range of approximately 5% below and 6% above the emission estimate of 765.4 Gg CO_2 Eq. For 2010, HFC emissions were estimated to be between 10,324.2 and 11,344.2 Gg CO_2 Eq. at the 95% confidence level; this indicates a range of approximately +/-5% around the emission estimate of 10,833.7 Gg CO_2 Eq.

Table 104. Quantitative Uncertainty Estimates for 1995 and 2010 HFC Emissions from Refrigeration/AC

Gas	Year	Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		(Gg CO_2 Eq.)	(Gg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
HFCs	1995	765.4	723.4	808.4	-5%	6%
HFCs	2010	10,833.7	10,324.2	11,344.2	-5%	5%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval and applied to the actual emission estimates calculated by the DECC Refrigeration/AC model (v9).

The higher uncertainty in the base year emission estimate relative to 2010 is due to the fact that emissions by end-use were estimated using the most recent data available—which was typically for year 2010—with back-casting methods or assumptions applied in cases where equivalent historical data were not available. For years beyond 2010, uncertainty will similarly increase relative to 2010, as future emissions are calculated based on projected equipment growth rates, refrigerant transitions, and changes in charge size and loss rates that are yet to be known.

Future improvements to the uncertainty analysis can be made by further exploring the uncertainty bounds associated with each functional form and employing parameter-, end-use-, and refrigerant-specific probability density functions. Additionally, the uncertainty model can be refined to eliminate the very slight discrepancy in calculated operational emissions compared to the DECC Refrigeration/AC model (v9) which exists due to the use of a functional form weighted average operational leak rate.

[24] @RISK input formulae were truncated for the variables percent refrigerant used, emission factors, and loss rates.

8 Future Model Updates

As described in the previous sections, significant updates have been made to DECC's refrigeration and air conditioning (AC) emissions model to improve accuracy, functionality, flexibility, and transparency. However, there are areas of the model that could still benefit from additional research and future updates. Specifically, areas for future work to improve GHG estimates or use for policy purposes are listed below.

8.1 GHG Estimate Improvements

1. **Further investigate consumption of R-404A vs. HFC-134a in key sectors:** Through comparison of the revised model's estimated consumption with the BRA production data, it was identified that the revised model may overestimate consumption of HFC-134a and underestimate consumption of R-404A. Although reasonable adjustments have already been made to the assumptions to account for this discrepancy, further research is needed to better understand and rectify the imbalance. Key sectors such as commercial refrigeration and industrial refrigeration should be further assessed to ensure that the assumed refrigerant transitions are representative of the UK market.
2. **Improve stock assumptions for condensing units:** In conducting research for this update, no information was available on the number of condensing units currently in use in the UK. As a result, disparate stock information for condensing units in the EU and A2 countries was scaled to the UK, which resulted in a large and uncertain range. Additional research in this area should be conducted to refine this assumption.
3. **Improve stock and charge size assumptions for industrial systems:** In conducting research for this update, limited information was available on the number and size of industrial refrigeration systems in the UK. The current estimate is primarily based on a survey conducted by Defra on the food production industry. While the information in this study is reliable and helps to characterise 75% of this end-use, it does not account for other types of industrial systems, such as those used by the chemicals industry. More research in this area should be conducted to better understand refrigerant usage in this end-use—in terms of the number of facilities in operation, and the average charge size per facility.
4. **Refine vehicle growth projections**: ICF attempted to obtain vehicle growth projections from the UK Department for Transport (DfT) but these were not made available in time. Growth projections should be refined if/when the projections become available from DfT.
5. **Improve operational leak rate assumptions for marine transport refrigeration:** Although information was generally available on transport refrigeration, no UK-specific industry information was provided for the marine transport refrigeration sector. Further efforts to solicit industry input on charge sizes and leak rates should be undertaken to corroborate the assumptions developed based on existing literature.
6. **Refine input assumptions as new industry data become available:** To develop the input assumptions for all end-uses, ICF relied on the most recent and relevant available information. However, as new research is continually being conducted on the refrigeration/AC sector, newly published or updated reports should be reviewed and considered for future model updates. For example, the final ERIE/Armines study ("1990 to 2010 refrigerant inventories for Europe") as well as the final EC report to be published by Caleb and SKM Enviros towards the end of 2011 ("Further Assessment of Policy Options for the Management and Destruction of Banks of ODS and F-Gases in the EU") could be reviewed for their relevance. (Draft inputs to both of these studies were considered in this analysis.)
7. **Assess future impacts of Regulation (EC) No. 842/2006:** In developing leak rate assumptions, the impact of the leak checking/repair provisions specified under Regulation (EC) No. 842/2006 on certain fluorinated greenhouse gases (the F-gas Regulation) was considered during this model update process. In light of the regulation as well as improvements in technologies, leak rates for most types of new equipment vintages are assumed to decrease over time; however, the impact of the regulation was not deemed to be significant enough to further affect leakage of existing equipment—at least not through 2010. Specifically, a version of the model was run assuming reduced leakage rates for existing equipment starting in 2010,[25] and this caused the model output to

[25] Existing equipment with a charge size of 3 kg or more was assumed to leak at the same rate as new equipment manufactured in 2010.

be about 10% lower than BRA refrigerant sales data in 2010 (compared to only 4% lower without this assumption). In future, however, leak rates of existing equipment should be lowered if the F-gas regulation (or any future EC or UK regulations) is found to produce more significant impacts with regards to lowering leakage from existing equipment stocks.

8. **Account for future EC and UK Regulations:** As Regulation (EC) No. 842/2006 is currently undergoing review, a future recast of the regulation is likely to yield new requirements that will require modifications to current modelling assumptions—such as those related to refrigerant transitions and/or emission rates (e.g., losses at disposal). For example, if the recast limits or phases out HFC consumption in certain end-uses, the transitions projected in the current model will need to be updated accordingly. Likewise, the UK could implement future regulations that will similarly affect model assumptions. Therefore, the policy landscape should be carefully tracked and properly considered in the model. .

9. **Update input assumptions based on IPCC (2006):** Currently the model relies on the default assumptions provided by the IPCC (2000) report when other data or industry estimates are not available. Once the IPCC inventory guidance is updated to allow the use of the 2006 default values, the model should be reviewed and updated, as appropriate, to incorporate the more recent default assumptions.

10. **Add a retrofit loss rate:** The model does not currently assume that any refrigerant losses occur during the retrofitting of ODS and HFC equipment, as data on such loss rates were not readily available. In reality, however, emissions will result from the recovery and transfer of refrigerant from equipment to cylinders during the retrofit process. Therefore, assumptions for retrofit loss rates should be developed—either universally across end-uses or tailored to specific equipment types. It should be noted, however, that the current model overestimates losses from ODS retrofitted equipment by roughly 2%, due to the model deficiencies associated with retrofit/phaseout dynamics; this modelling deficiency (described further under item 13, below) should be addressed prior to adding any retrofit loss rate assumptions for ODS equipment. The IPCC does not provide guidance in terms of estimating retrofit loss rates.

11. **Account for export of disposed equipment:** To the extent that a significant number of equipment is exported outside of the UK at end-of-life, the model may be over-estimating refrigerant losses from such equipment at disposal. This may be an issue for transport refrigeration equipment, light duty MACs, Other MACs, and/or other equipment.

12. **Enhance the uncertainty analysis**. Improvements to the uncertainty analysis can be made by further exploring the uncertainty bounds associated with each functional form and employing parameter-, end-use-, and refrigerant-specific probability density functions. Additionally, the uncertainty model can be refined to eliminate the very slight discrepancy in calculated operational emissions compared to the DECC Refrigeration/AC model (v9) which exists due to the use of a functional form weighted average operational leak rate.

8.2 Improvements for Policy Purposes

13. **Develop tailored assumptions for ODS and natural refrigerants:** Charge sizes and loss rates do not currently vary in the model by refrigerant type, but rather are representative of the average charge and loss rates for HFC equipment. Further research should be conducted to tailor these assumptions by refrigerant type to improve emissions estimates of the non-HFC refrigerants.

14. **Incorporate climate impacts of ODS and natural refrigerants:** Although the model has been updated to account for the market penetrations of non-HFC refrigerants, the GWPs of CFCs, HCFCs, and natural refrigerants (i.e., ammonia, carbon dioxide, and hydrocarbons) are currently not accounted for in the emissions calculations. In the future, DECC may want to consider adding a feature to include the climate impacts of ODS and natural refrigerants in the output of the model—without including such impacts in the CRF output.

15. **Improve the modelling of the ODS phaseout:** Per Regulation (EC) No 1005/2009, the UK is required to phaseout the use of certain ODS refrigerants by specific dates. For instance, the use of new HCFCs in most new equipment was banned starting in 2001, and HCFCs will be prohibited for use in servicing starting in 2015. In light of increasing HCFC scarcity and rising costs, and to avoid the premature retirement of HCFC equipment, the model assumes a large portion of existing HCFC equipment get retrofitted. But the model is currently limited in the extent to which it can fully account

for the complex market dynamics at play—which could in reality involve destruction of HCFC refrigerant recovered from retired equipment and/or illegal use of HCFCs beyond 2015 (neither of which are modelled in the current framework). As a result, the model calculates the necessary adjustments for operational emissions from retrofitted CFCs and HCFCs using a calculated operational emission rate. This comes within 2% of the correct emission rate, and the model forces the bank to reach zero in the appropriate year to compensate for the fact that these adjustments cannot be calculated exactly. Additional changes to the programming of the model could be undertaken to more accurately account for the market dynamics associated with ODS retrofits and phaseouts. These improvements would likely require additional use of VBA, which could potentially reduce calculation transparency. Please see Section 2.2.3 for additional information about the ODS phaseout calculations. It should be underscored that these updates would not affect HFC emission projections.

16. **Expand the model to include energy efficiency considerations:** To enable the DECC model to better serve as a policy tool, consideration of the energy performance associated with different refrigerant types across end-uses could be added to the model. EPEE suggested that this consideration be added to the model given that energy efficiency is the key driver in GHG emissions. This would require research on how energy consumption differs when shifting from one refrigerant to another across the various refrigeration/AC applications and climatic regions.

Appendix A. Industry Stakeholders

The organisations listed in Table 105 were contacted by ICF by email and/or phone to provide input on model assumptions. Specifically, the list includes priority contacts identified for outreach in July 2011 for developing key assumptions, as well as organisations identified for outreach in late August/early September for vetting those draft assumptions. The table indicates those contacts that provided input.

Table 105. Summary of Stakeholders

Organization	Contact Name	Relevant End-Use	Provided Feedback?
A-Gas	Ken Logan Francis Burraston	All	No
ACEA (European Automobile Manufacturer's Association)	Hermann Meyer	Mobile AC	No
Air Conditioning and Refrigeration European Association (AREA)	Joop Hoogkamer	Small AC, Condensing Units, Chillers, Supermarkets	No
Atlantic Consulting	Eric Johnson	Heat Pumps	Yes
Association of Manufacturers of Domestic Appliances (AMDEA)	Stuart MacConnacher	Domestic refrigeration	No
Association of Train Operating Companies (ATOC)	Richard Wallace	Transport (trains)	No
BRE	Roger Hitchin	All	Yes
British Chamber of Shipping (BCS)	Edmund Brookes	Transport Refrigeration (Ships)	No
British Vehicle Salvage Association	A. Greenouff	Mobile AC	No
Calor	Paul Blacklock	All	No
Carrier (United Technologies)	Darcy Nicolle	Building AC, chillers, small AC, transport (land and non-land)	Yes
Dailkin	Hilde Dhont	Heat pumps, building AC, industrial refrigeration	Yes
Daimler Chrysler	Jane Steer	Mobile AC	No
Danfoss Ltd	Curtis Mills	Heat pumps	Yes
Du Pont	Jorge Dieguez	All	No
Earthcare Products	Nicholas Cox	Stationary AC (non-chillers)	Yes
European Partnership for Energy and the Environment (EPEE)	Denis Bonvillain	Small AC, Condensing Units, Chillers, Supermarkets	Yes
Food and Drink Federation	Stephen Reeson	Condensing Units, Small Refrigeration Units, Industrial refrigeration	Yes
FoodDrinkEurope	Tove Larsson	Condensing Units, Small Refrigeration Units, Industrial refrigeration	No
Ford	Steve Cautley	Mobile AC	No
Foster Refrigeration	Chris Playford	Supermarket Systems, Condensing Units	No
Ground Source Heat Pump Association (GSHPA)	David Matthews	Heat pumps	No
Heat Pump Association (HPA)	Tony Bowen	Heat pumps	No
Honeywell	Tim Vink Paul Sanders	All	Yes
Ingersoll Rand	Jeff Berge	Refrigerated Transport- Land	Yes

International Association for Cold Storage Construction (IACSC)	Jimmy Bittles	Condensing Units, Transport	No
LG Electronics Europe	Yu-Mi Mun	Small AC	No
Mark & Spencer	Bob Arthur	Supermarket Systems, Condensing Units, Small Refrigeration Units,	Yes
Mexichem Fluor	Andy Lindley	All	Yes
Motor Vehicle Dismantlers Association	Duncan Wemyss	Mobile AC	No
Mitsubishi Electric	Philip Ord James Hobson	Small AC, Heat pumps	No
Overton Recycling	Dean Overton	EOL for all refrigeration equipment	Yes
Sainsburys	John Skelton	Supermarket Systems, Condensing Units	No
Samsung	MaDonald	Small AC	No
Sanden	Georges Khoury	Mobile AC	Yes
SKM Enviros	Ray Gluckman	All	Yes
Star Refrigeration	David Blackhurst	Industrial refrigeration	Yes
Tesco	John Birch	Supermarket Systems, Condensing Units	No
Tesco	Brian Francis	Supermarket Systems, Condensing Units	No
Thermo King	Sam Dutta	Refrigerated Transport	Yes
TRANSFRIGOROUTE INTERNATIONAL		Transport Refrigeration	No
Trane	Aidan Flannery	Air-conditioning Chillers	Yes
Waitrose	Les King	Supermarket Refrigeration	No

Appendix B. 2010 Input Assumptions by End-Use

Table 106. Summary of 2010 Input Assumptions by End-Use

Application		2010 Parameters							
CRF Sector	UK Category	Total Stock (units)[a]	Total Sales (units)[a]	Lifetime (years)	Charge (kg)[a]	Refrigerants in New Equipment	Manufacturing Loss Rate	Operational Loss Rate	Disposal Loss Rate
Domestic Refrigeration	Domestic Refrigeration	40,430,000	2,939,680	15	0.10	HFC-134a, HCs	0.6%	0.3%	35%*
Commercial Refrigeration	Small Hermetic Stand-Alone Refrigeration Units	2,400,000	247,400	10	0.5	HFC-134a, R-404A, R-407C, HCs	1%	1.5%	40%*
	Condensing Units	600,000	47,440	14*	5*	HFC-134a, R-404A, R-407A, R-407F,R-410A, R-507, HCs	2%	10%	15%
	Centralised Supermarket Refrigeration Systems	109,100,000 (m^2)	10,135,722 (m^2)	18*	0.26 (kg/m^2)	HFC-134a, R-404A, R-407A, HCs, R-717, R-744	2%	18%	8%
Transport Refrigeration	Land Transport Refrigeration	87,210	13,506	7	4	HFC-134a, R-404A	0.2%	15%	20%
	Marine Transport Refrigeration	527	30	25*	1,500*	R-404A, R-407C, R-717	1%	40%	30%
Industrial Refrigeration	Industrial Systems	20,000	764	25*	65	HFC-134a, R-404A, R-407C, R-410A, R-507, HCs, R-717, R-744	1%	8%	15%
Stationary Air-Conditioning	Small Stationary Air Conditioning	4,590,202	615,160	13	1.5	R-407C, R-410A	0.5%	3%	30%
	Medium Stationary Air Conditioning	630,000	52,268	15	15	R-407C, R-410A	1%	6%*	30%
	Large Stationary Air Conditioning (Chillers)	40,000	2,129	18	180	HFC-134a, R-407C, R-410A, R-717	0.5%	3%	20%
	Heat Pumps	20,270	9,632	15	3	HFC-134a, R-404A, R-407C, R-410A	1%	6%*	35%*
Mobile Air-Conditioning	Light Duty Mobile Air Conditioning	27,859,726	1,340,061	15	0.73	HFC-134a	0.5%	10%	30%
	Other Mobile Air Conditioning	499,168	87,502	10	4*	HFC-134a, R-407C	0.5%	10%	30%

[a] Except where otherwise noted.
* Estimates fall outside of the IPCC (2000) range but are in line with UK- and/or EU-specific estimates provided by industry or in the published literature.