Proklima

Banks and Emissions of CFC-11 and CFC-12

Country data and possible consequences for global modelling

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Content

Abbreviations

BMU	German Federal Ministry for Environment, Nature Conservation and Nuclear Safety
CFC	Chlorofluorocarbons
EOL	End-of-life
EPS	Expanded Polystyrene
FTOC	Rigid and Flexible Foams Technical Option Committee
GHG	Greenhouse Gases
GIZ	Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
HCFC	Hydrochlorofluorocarbons
HPMP	HCFC Phase-out Management Plan
IKI	International Climate Initiative
MP	Montreal Protocol
nA5	non-Article 5 countries
ODS	Ozone Depleting Substances
PU	Polyurethane
RAC	Refrigeration and Air-conditioning
TEAP	Technical and Economic Assessment Panel
UN	United Nations
UNEP	United Nations Environment Programme
XPS	Extruded Polystyrene

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1 Introduction

Chlorofluorocarbons (CFCs) were widely used as refrigerants and foam blowing agents. During its peak consumption in the 1990s, it is estimated that up to 430 kilo tonnes of CFC (GIZ, 2018) were added to the bank annually. CFCs are ozone depleting substances (ODS) and their bank is defined as the amount of substance contained in appliances and other products that have not been released to the atmosphere yet[1]. Due to the CFC phase-out, accomplished under the Montreal Protocol within non-Article 5 (nA5) countries[2] in 1996 and Article 5 (A5) countries in 2010, the CFC bank is not increasing any longer. However, the size of the CFC bank in foam products (and to a lesser extend in refrigeration and air conditioning equipment) is believed to be still considerable. Several models estimate the remaining CFC bank on a global scale (Ashford et al., 2004) in the Assessment Reports of the Rigid and Flexible Foams Technical Option Committee (FTOC, 2006, 2010, 2014, 2018; GIZ, 2018). Nevertheless, the assumptions of those models, although state of the art in terms of chemical behaviour, often disregard (lack of adequate) recycling practices, resulting in several uncertainties. Thus, the debate on the remaining CFCs in banks, and the resulting emissions, is still ongoing.

This study intends to contribute to the debate by

- Shedding light on individual country's estimated remaining CFC bank and their handling. The focus are CFC-11 and CFC-12 in building foams.
- Investigating the fit of model assumptions to found practices and carrying out a sensitivity analysis on selected parameters.

This paper is part of the project 'Management and Destruction of Existing Ozone Depleting Substances Banks' funded by the German Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMU) under its International Climate Initiative (IKI) and implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

1.1 Problem outline

There are several uncertainties attached to CFC consumption, banks and resulting emissions. Most of them are already stated in the report of the Technical and Economic Assessment Panel (TEAP, 2006), and revisited in the light of possible sources of the unexpected CFC-11 emissions in TEAP (2019), where atmospheric measurements of selected CFCs and Hydrochlorofluorocarbons (HCFCs) were used to estimate global emissions of those substances. These emissions were compared to the estimated emissions derived from reported consumption, use patterns and emission factors. The effect of the uncertainties listed below is most severe to CFC-11, where atmospheric measurements hint to higher emissions than bottom-up estimates, but are generally applicable to CFC-12 and other less commonly used CFCs as well. The uncertainties are related to

1) the underestimation of emissive uses

- Keeping the overall production constant, this would reduce the bank size. A higher share of emissive uses means that more CFC was emitted in the year it was used and thus less CFC entered the bank.
- There is doubt voiced by TEAP that all production was reported. This could mean that even with an underestimation of emissive uses, the lacking amount is somewhat balanced by the incomplete reporting of production. The amount assumed to have reached the bank is thus not affected (also compare next bullet).

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[1] Commonly, the bank is distinguished in the reachable bank, i.e. CFC contained in products that have not entered the waste stream and the non-reachable bank that comprises CFC in products already landfilled or otherwise dumped uncontrolled.

[2] In Article 5 of the Montreal Protocol, Article 5 countries are defined as 'Any Party that is a developing country and whose annual calculated level of consumption of the controlled substances in Annex A is less than 0.3 kilograms per capita on the date of the entry into force of the Protocol for it […]'. Non-Article 5 countries are mostly developed countries, while Article 5 are developing ones.

2) underreporting of previous consumption, particularly for emissive uses

- The added consumption for emissive uses does not change the amount of gas that entered the bank. Thus, a higher consumption that was emitted in the correpsonding year does not affect the bank size.
- Again, this raises the question on complete reporting of production (as above).

3) underestimation of atmospheric lifetime and thus overestimation of emission based on atmospheric mole fractions

- The easiest way to reconcile the two datasets, but claimed not to be sufficient to explain the gap between atmospheric measurements and estimated emissions.

4) uncertainties of emission patterns from insulation foam in buildings

- This depends on building demolition timing and applied recycling practices.
- Little information is published on this topic.
- The effect on current CFC-11 and CFC-12 emissions could be substantial.

5) uncertainty on lifetime of refrigerators using CFC-12 as refrigerant and CFC-11 as insulation

- Longer lifetimes as previously modelled seem likely.
- The contribution to current CFC-11 and CFC-12 emissions depends on recycling practices.

This study looks at possible current banks of CFC-11 and CFC-12 in building insulations foams and appliance foams in domestic refrigerators based on selected country cases.

1.2 Approach of this study

This study investigates the currently applied assumptions of global CFC banks models and compares it with data collected in specific countries. The assumptions used in the global ODS banks model presented in the paper “Global banks of ozone depleting substances – A country-level estimate”(GIZ 2018), further referred to as “our model”, are reviewed in the light of the findings from country specific ODS bank inventories. Further, assumptions made by the TEAP in its foam bank model are researched and compared. Additional research on CFC contained in discarded refrigerator and building foams are carried out in selected individual countries within this study.

Based on these findings, a sensitivity analysis of identified ranges of assumptions is carried out. The results are intended to illustrate possible ranges of existing CFC banks and the related emissions.

The focus of this study is CFC-11 in building foams and appliance foams. CFC-12 is studied as blowing agent of Extruded Polystyrene (XPS) foam boards, which are also used as building foam. Refrigerators containing CFC-11 in the foam, usually contain CFC-12 as refrigerant. CFC-11 that is still used in some centrifugal chillers is not included in this study.

The banks of the refrigeration and air-conditioning (RAC) sector are defined as the refrigerant contained in RAC appliances in use, while the insulation foam used in RAC appliances is part of the foam bank.

2 Country cases

In this chapter, country experiences gathered within the ODS banks management project are summarized with the aim to draw a conclusion for the modelling parameters applied in our model. Additional research on current practices when dealing with CFC waste is conducted within selected nA5 countries country cases; Again with the aim to compare the findings with the modelling parameters.

2.1 Summary from ODS bank inventories

While our global model developed in the framework of the ODS Banks project follows a Tier 1[3] approach, detailed Tier 2 inventories of the RAC sector were carried out in all five partner countries of the ODS banks management project. Special focus of these inventories is the determination of the amount of ODS (CFC and HCFC) that has not entered the waste stream yet and is therefore potentially available for management. The findings for CFCs of both approaches are presented in Table 1. The top down approach (Tier 1) as part of our global model does not predict any CFC bank for the RAC sector in 2014, while the country analysis (based on Tier 2) points to a different result: Although rapidly declining, CFCs (CFC-12) are still present in the RAC sector. The foam sector was not studied during the country inventories. A detailed description of data sources of this model can be found in section 3.1.

Table 1: Banks of CFC in metric tonnes, as determined in country inventories carried out within the project "ODS banks management" (Tier 2) and from the global model (Tier 1)

In metric tonnes	Tier 1		Tier 2			
	RAC bank	Foam bank	RAC bank			Foam bank
	2014	2014	2015	trend 2020	Applications	
Colombia	none	1260	90	50	mainly mobile AC, domestic refrigeration and transport refrigeration	not studied
Dominican Republic	none	260	0	0		not studied
Ghana	none	35	55	15	mainly refrigerators	not studied
Iran	none	15000	0	0		not studied
Tunesia	none	1700	26	0	refrigerators, commercial standalones	not studied

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[3] Inventories can be conducted at different levels of disaggregation. Tier 1, (also called top-down approach) is more general than Tier 2 and studies a sector as a whole. In our model, the entire RAC or foam sector, using averaged emission patterns to calculated banks and emissions. The more detailed Tier 2 approach (or bottom-up approach) studies the applications in detail. In the ODS banks inventories, 19 different sub-applications of the RAC sector were studied, such as commercial condensing units, commercial centralized system, single-split AC units, ducted AC units, chillers, etc.

2.2 Research on existing information in selected countries

The majority of the remaining CFC bank is contained in foam (TEAP, 2006, 2019). Therefore, very specific desk research was undertaken in the framework of this study to gather information on what is known about the country specific CFC banks in foam, focusing on insulation foam in buildings and appliance foam. The majority of CFC banks in foam are located in nA5 countries. This is inferred from a larger consumption of CFC foam blowing agents than in A5 countries. Country cases were selected based on initial evidence of some research activity: one large country for Europe (Germany); one smaller (Austria); and North America (USA).

2.2.1 Germany

Insulation foam in buildings

Estimates on CFCs in building foams in Germany are available for 2009 (Obernosterer, 2012). The same study concludes that the majority of CFC in building foams are contained in very few applications: Polyurethane (PU) rigid panels, PU sandwich panels and PU pipe insulations, which make up more than 75 % of the bank. Extruded polystyrene (XPS) boards and sandwich panels constitute a minor fraction.

A study conducted by the Fraunhofer Institute (Albrecht and Schwitalla, 2015) that focused on recycling of thermal insulation composite systems and thus on expanded polystyrene (EPS) and partly also on XPS boards concluded that the amount of insulation foam reaching the waste streams could not be determined from field research.[4] The models for future waste amounts are based on waste statistics and information from dedicated associations and only covered EPS boards, which do not contain CFCs. For 2012, 41 kilo tonnes of waste from EPS and XPS insulation boards (weight of foam boards) were estimated (Consultic, 2012).

Foam containing CFC, HCFC or HFC has to be treated in waste incineration facilities. This is a consequence of the Geman law on circular economy (Kreislaufwirtschaftsgesetz, KrWG, 2012)[5], which transfers the EU Directive 2008/98/EC[6] on waste into national law.

Appliance foam

The recycling of refrigerators containing CFCs was subject of several studies. The fraction of refrigerators containing CFC within the total amount of waste refrigerators decreased from about 85 % in 2008 to around 50 % at present (LAGA, 2018). Additionally, several recycling companies dealing with waste refrigerators were contacted by phone. Gathering information was difficult, as the responsible persons were either hard to reach or were reluctant to provide information via telephone. Those who did provide information, confirmed the findings in the literature, that about 50 % of treated refrigerator still contain CFCs.

The sale of refrigerators containing CFC has stopped in 1994. This infers lifetimes of refrigerators containing CFC can be estimated to be 25 years and longer. The Act Governing the Sale, Return and Environmentally Sound Disposal of Electrical and Electronic Equipment (Electrical and Electronic Equipment Act – ElektroG) specifies specific obligations for all relevant stakeholders (manufacturers, trade, municipalities, owners, disposers). Due to the established collection infrastructure the risk of an

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[4] The authors report that conducted interviews with recycling companies did not enable conclusions on the total amount of recycled amounts.

[5] Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Law to promote circular economy and environmentally sound treatment of waste), retrieved from: http://www.gesetze-im-internet.de/krwg/index.html

[6] DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste, retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN

Summary table

Table 2: Summary of current information gathered for CFC banks in Germany

	Building foam	Appliances
Information on bank size	~100 kilo tonnes of CFC-11 ~14 kilo tonnes of CFC-12 (both estimates for 2009)[7]	Not stated in analysed documents
Information on sales used for bank build-up	XPS: use of CFC-12 until 1989 PU rigid foam boards: use of CFC-11 until 1994	Sales of CFC containing appliances ended in 1994[8]
Shares and trends in current waste stream	Not known[9]	2008: 80–90 % CFC containing appliances[10] 2012/2017: ~50 % CFC containing appliances[5] 2019: 40–50 % CFC containing appliances[11]
Recycling practices	CFC containing foams need to be collected separately and treated as hazardous waste	Automated degassing and shredding with collection of blowing agent
Estimated lifetime	20 – 60 years for thermal insulation composite systems[12]	Not stated in analysed documents, 25 years are inferred
Estimated emission factors from bank [% of initial content]	Use emissions: CFC-12 from XPS boards: 1.25 % CFC-11 from PU rigid foam: 0.35–0.69 %	Negligible amounts
Estimated end of CFC emissions from banks	No statement found	No statement found

inappropriate disposal is reduced, for example with household waste, and a more extensive recycling of the electronic appliances is enabled.

2.2.2 Austria

Insulation foam in buildings

Austria has taken considerable effort to quantify the ODS bank contained in building foam. Several studies, the last issued in 2007 have assessed the sales of insulation foam and the resulting banks, as well as possible ways of dealing with the waste. The above-mentioned study by Obernosterer et al. (2007) covers PU panels, sandwich panels and pipes, as well as XPS boards and estimated the emission mitigation potential of four different scenarios of waste management. Another study by Eibensteiner (2016), focussing on EPS and partly also on XPS as building insulation analysed the lifetime of insulation foam in buildings and found sources of considerably divergent numbers between 25 and 60 years. The authors concluded that most estimations are in the range between 30 and 50 years.

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[7] Obernosterer 2012

[8] Dehoust and Schüler (2007)

[9] At time of writing, no answer from the German Federal Environment Agency (UBA)

[10] LANUV (2009)

[11] Information from interviews

[12] Albrecht and Schwitalla (2015)

These assumptions led to the conclusion that all XPS boards possibly reach the waste stream by 2100.

The removal of insulation foams that contain CFC, HFCF or HFC from buildings prior to the demolition of the building is obligatory since 2017[13]. The foam is to be treated as hazardous waste and is usually thermally destructed.

Appliance foam

There is only one recycling company in Austria that deals with waste refrigerators. A study conducted in 2008 estimated the share of CFC containing appliances for 2008 at 83 % and projected a decline to 8 % in 2020 (LANUV, 2009). Due to obligatory recycling of refrigerators including the recovery and destruction of foam blowing agents, all waste refrigerators are treated accordingly. We can therefore conclude that CFC emissions from appliances are largely avoided.

2.2.3 United States of America

According to the 2019 GHG inventory, Annex 3.9 (EPA, 2019), the CFCs bank decreased from 770 kilo tonnes in 1995 to 120 kilo tonnes in 2017. The emissions of CFC according to the same inventory (Annex 6.2) was 232 kilo tonnes in 1990 and

Summary table

Table 3: Summary of current information gathered for CFC banks in Austria

	Building foam	**Appliances**
Information on bank size	17.6 kilo tonnes of CFC-11 4.8 kilo tonnes of CFC-12 (both estimates for 2010)[14]	Not stated in analysed documents
Information on sales used for bank build-up	Use of CFC as blowing agent in XPS boards stopped in the early 1990s[15], research was done among producers to estimate sales	Sales of CFC containing appliances ended in 1994[16]
Shares and trends in current waste stream	Trends for CFC bank projected until 2100[10]	2005: ~75 % CFC containing appliances[12]
Recycling practices	Separate collection and treatment is obligatory	Automated degassing and shredding with collection of blowing agent
Estimated lifetime	Average lifetime of insulation: 46 years Non-residential buildings: 37 years Commercial residential building: 43 years Private residential building: 51 years[11]	Not stated in analysed documents
Estimated emission factors from bank [% of initial content]	28 % during use (normal building lifetime) 10 % during demolition	negligible
Estimated end of CFC bank	Not stated in analysed documents	Not stated in analysed documents

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[13] 290. Verordnung: Änderung der Recycling-Baustoffverordnung, retrieved from: https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20009212

[14] Obernosterer et al. (2007)

[15] Eibensteiner (2016)

[16] Tesar and Öhlinger (2009)

27 kilo tonnes in 2017. This implies that uncontrolled CFC emissions lead to a decrease of the bank.

Insulation foam in buildings

According to Vetter and Ashford (2011), ODSs and HFCs from foam applications accounted for 61 % of the total (ODS and HFC) banks in the USA in 2005. This is expected to be greater in 2019, as building foam has a long lifetime and they are not destroyed or recycled after building demolition. In 2009, the most prevalent practice for the foam coming from demolitions, was to be land filled together with other mixed construction and demolition waste. Lifetime for buildings can vary from 25 to 70 years. The annual leakage rate, the leakage lifetime, and the loss at disposal values assumptions used by the US government in their Vintage Model for different types of foam can be seen in table A-151, annex 3.9 of the 2019 GHG inventory, which is partly reproduced in Table 4.

A detailed study of foam banks is not available for the US as whole. A study on Californian foam banks (Vetter and Ashford, 2011) estimates that in 2020, the CFC bank will account for more than 50 % of the total bank of CFC, HCFC and hydrofluorocarbons (HFCs) in terms of CO_2 equivalents. These numbers include the CFC bank in building insulation foam, both, the ones that are still in the building, and the insulation foam already landfilled after demolition. In absence of a regulation, landfilling of insulation foam without any recovery is the common practice.

Appliance foam

In the US, it is not allowed to vent any refrigerant into the atmosphere during installation, service, or retirement of equipment (e.g., appliances)[17]. Therefore, it must be recycled, reclaimed or destroyed. Nevertheless, there are no regulations about the recovery of blowing agent from the insulation foam. According to Vetter and Ashford (2011), only 14 % of the discarded refrigerators were totally treated in 2008, including the foam, 39 % were re-used and for the rest the foam was landfilled.

Due to the shorter lifetimes of appliances compared to buildings, most of the equipment containing

Table 4: Emission patterns of foam types, as modelled in the EPA Vintage Model (EPA, 2019)

Foam Type	First year release (%)	Release rate (%/year)	Leakage lifetime (years)	Lifetime of foam (years)	Total remaining at decommissioning (%)	Assumed potential release (%)
PU integral skin	95 %	2.5 %	2	N.A.	0 %	100 %
PU cont. panel	8.8–11.25 %	0.50 %	50	50	63.75–66.5 %	100 %
PU disc. panel	8.8–11.25 %	0.50 %	50	50	63.75–66.5 %	100 %
PU appliance	4 %	0.25 %	14	14	40 %	47 %
PU disc. block	33 %	0.88 %	15	15	54 %	100 %
PU spray	15 %	1.5 %	50	50	10 %	100 %
XPS board	25 %	0.8 %	25	25	56 %	100 %
PU flexible foam	100 %	0.0 %	1	N.A.	0 %	100 %

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[17] Clean Air Act, Section 608, retrieved from: https://www.govinfo.gov/content/pkg/USCODE-2013-title42/html/USCODE-2013-title42-chap85-subchapVI-sec7671g.htm

CFCs is expected to be retired by 2020 (Vetter and Ashford, 2011). Nevertheless, appliances such as refrigerators that also contain foam can contribute to the CFC banks for a longer time, as foams continue to release CFCs when landfilled. This is reflected in the emission patterns shown in Table 4, where 53 % of the blowing agent is anticipated to be emitted at a rate of 2.0 %/year post-disposal.

The low recycling rates show that voluntary recovery of foam blowing agents is not sufficient to reach high recycling rates.

Summary table

Table 5: Summary of current information gathered for CFC banks in the USA

	Building foam	Appliances
Information on bank size	200 million tonnes of CO_2-eq. estimated for 2020 and accounting with the waste stream for the state of California[18]	21 million tonnes of CO_2-eq. estimated for 2020, mainly accounting with the waste stream for the state of California
Information on sales used for bank build-up	CFC usage for insulation foam stopped in 1994	CFC usage for appliance foam stopped in 1994
Shares and trends in current waste stream	No values in % of CFC, but in 2020 the CO_2-eq bank will be still dominated by CFC foams in the waste stream	No values in % of CFC, but in 2020 the CO_2-eq bank will be still dominated by CFC foams in the waste stream
Recycling practices	In 2009 most of the building foam was left in landfills together with other construction and demolition material A recent change in recycling practises is not expected	Refrigerant has to be recycled or destroyed, but not the foam. In 2008, 14 % of the discarded refrigerators were properly recycled
Estimated lifetime	For low rise residential building: 30 years For non-residential buildings: From 25 to 70 years Nevertheless, depending on the foam technology, the annual leakage will be different, leading to different quantities at the time of disposal. See the assumptions for the Vintage Model in Table A-151 of Annex 3.9[19]	It will depend on the appliance. Domestic refrigerators have an average lifetime of 14 years[14]. The annual leakage is 0.25 %, all the rest of blowing agent is released after disposal, unless it is partly recycled
Estimated emission factors from bank (% of initial content)	It will depend on the type of foam (Vintage Model). For instance, for the XPS Boards: First year emissions: 25 % Use emissions: 18.75 % (25 years) Blowing agent left at EOL: 56.25 %	For Domestic Refrigerator PUR Foam: First year emissions: 3.75 % Use emissions: 3.5 % (25 years) Blowing agent left at EOL: 92.75 %
Estimated end of CFC emissions from banks	Not stated in analysed documents	Not stated in analysed documents

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[18] Vetter and Ashford (2011)

[19] EPA (2019)

3 Implications for the global CFC banks model

This chapter brings together the findings of the country cases with the model assumptions of two foam banks models: our (previous) Tier 1-model and the model used by TEAP (2006, 2019). The country evidence, mostly regarding the lifetime of foam in both appliances and buildings is compared to the modelling parameters.As a result, a new set of modelling parameters is presented at the end of the chapter.

3.1 Summary of data sources

3.1.1 Our banks model

Our previously developed global Tier 1-model is based on the consumption data that all parties to the Montreal Protocol report under Article 7 to the Ozone Secretariat. Assumptions deducted mainly from the sector-split of large countries as stated in their HCFC Phase-out Management Plans (HPMPs) are taken to allocate the consumed ODS to RAC and foam sectors. There is no further disaggregation into different applications within the sectors. Trade of pre-charged equipment is factored in by adding and deducting estimated charge sizes of imported and exported equipment as reported to the UN Comtrade database. Assumptions of an average equipment lifetime and ODS emissions during manufacture and use result in a model of ODS banks remaining in each country. A summary of assumptions is presented in chapter 3.2, a detailed model description is contained in GIZ (2018).

3.1.2 Findings from ODS inventories in project partner countries

The country inventories infer longer lifetimes for RAC equipment, especially for household refrigerators containing CFCs. This hints that the lifetime of CFCs in the bank might be underestimated in our previous model. Since the Tier 1 does not differentiate between different RAC application, it is difficult to determine the balanced average lifetime across all applications.

The foam sector was not part of the five country inventories (Colombia, Dominican Republic, Ghana, Iran, Tunisia) covered by the ODS banks project; therefore, no direct conclusion can be drawn. However, the issue with potentially underestimated lifetimes will be taken up in section 3.2 for the foam sector too.

3.1.3 Country research of this study

The aim on the country research is to collect information on actual country specific bank and waste amounts as well as recycling procedures for CFC containing foam to compare these country specific values to the assumptions of our global ODS banks model.

Although specific estimates of CFC banks for Germany and Austria are only available for 2009 and 2010 respectively, there is no doubt that CFCs in the foam bank are still present in these countries. This contradicts the projection by our model, where the CFC foam bank in Germany is predicted to be zero for 2011. For Austria, the CFC bank is predicted to be zero in 2005. For the USA, no numbers are available, but the situation in California, where still a considerable CFC foam bank exists, is assumed to be representative for the whole of the USA. Our model predicted no CFC bank for 2011. This implies that the assumed lifetimes for foam products in our previous model are too short.

3.1.4 Model on foam banks employed by the FTOC and TEAP

Substantial work regarding the status of global foam banks was conducted by the TEAP and its Technical Options Committee. Therefore their set of modelling parameters is included in this analysis. The development of their model of foam banks was started in the 1970’s with detailed data set being published by Ashford et al. in 2004. Later Assessment Reports of the Foams Technical Options Committee (FTOC) (2006, 2010, 2014,

Table 6: Application specific emission factors of common foam types. Source: Ashford et al. (2004)

Foam Type	First year release (%)	Release rate (%/year)	Time to total release [years]	Lifetime of foam (years)	Total remaining at decommissioning (x)	Assumed potential release (%)
PU integral skin	95 %	2.5 %	2	15	0 %	100 %
PU cont. panel	8 %	0.50 %	105	50	67.5 %	100 %
PU disc. panel	13 %	0.50 %	95	50	62.5 %	100 %
PU appliance	4 %	0.25 %	224	15	92 %	100 %
PU injected	6 %	0.25 %	215	15	90 %	100 %
PU cont. block	35 %	0.75 %	33	15	54 %	100 %
PU disc. block	40 %	0.75 %	27	15	49 %	100 %
PU cont. lam.	10 %	1.5 %	33	50	15 %	100 %
PU spray	25 %	1.5 %	23	50	0 %	100 %
Phen. cont. lam.	10 %	1.5 %	60	50	15 %	100 %
Phen. disc. Block	40 %	0.8 %	80	15	49 %	100 %
XPS board	25 %	2.5 %	30	50	0 %	100 %
PE board	90 %	5.0 %	2	50	0 %	100 %

2018) as well as the Special Report: Safeguarding the Ozone Layer and the Global Climate System (SROC, 2005) are citing from this data set. FTOC stated that the model was adapted to allow banks and emission estimates up to 2020. However, these adaptions were not specified. TEAP's task force (TF) on unexpected CFC-11 emissions presented an elaborated bottom-up model based on previous work and further investigations, along with a sensitivity analysis and presented the findings in its Taskforce Report (TEAP, 2019).

As described in Ashford et al. (2004), the model is based on bottom up consumption data per region and separated for different foam applications. Furthermore, the authors developed a set of application-specific emission factors for first year emissions, annual emissions, product lifetime and time span until the blowing agent is completely released as shown in Table 6. The latter is varied for different end-of life scenarios including shredding (with and without blowing agent capture), re-use and landfilling. However, the authors stated that no reliable information on EOL-practices were available. The sensitivity of the model was tested, and the estimated non-reported production was identified as the largest source of error. As a reaction, production figures were reconciled with the UNEP database on each country's reported consumption. This measure was found to rectify the issue to a large extend.

The assumptions on lifetimes and emission factors as presented in Ashford et al. (2004) are specific for each foam application and take into account that bank and emissions might persist after the equipment has reached the waste stream.

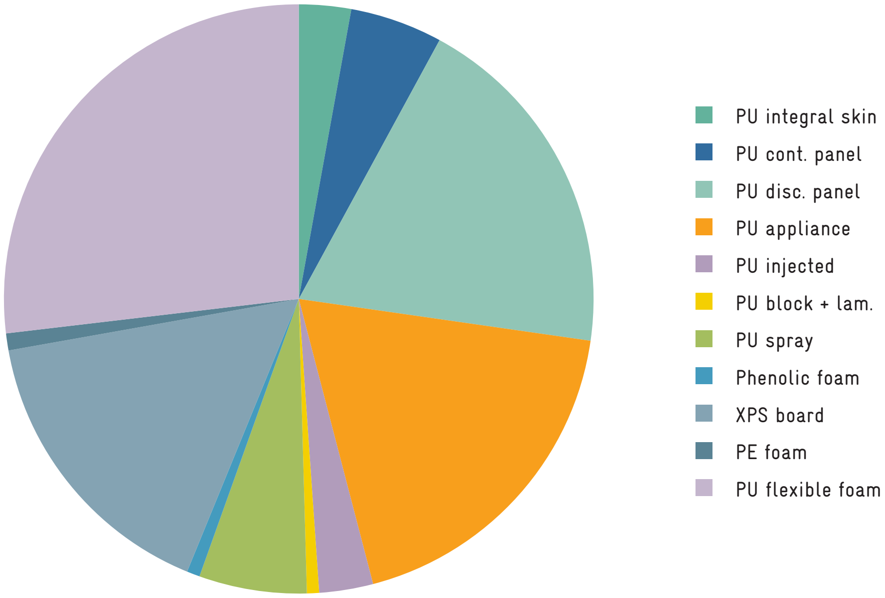
Building on previous findings, the TEAP TF defined their set of factors to model the CFC-11 banks. The aim of their work is to identify possible and out rule unlikely sources of the unexpected CFC-11 emissions that were reported by Montzka (2018). Although the ultimate aim is different, their work included several considerations useful for this study, such as likely emissions from CFC-11 foam banks. The sensitivity analysis performed by the TF shows that largest effects are caused by the variation of two parameters. Since the majority of CFC-11 is contained in closed cell foam, varied emission factors of the foam bank have a large effect on the overall CFC-11 bank and emissions. The second parameter with a large effect is the overall amount of produced CFC-11. The data set on reported production from AFEAS and UNEP (after 1989) was increased by up 40 % to illustrate this effect, even though TEAP TF stated that such a high under reporting is highly unlikely (TEAP, 2019). A combined variation of production and emissions rates results in considerable variation of bank and emissions. In 2020 the calculated bank size varies between close to zero for the high emission/reported production scenario to about 2000 kt for the low emission/40 % increased production scenario. The applied emission factors are high compared to other values found in literature and are explained by TEAP by referring to expert opinions who claim that emission from closed cell foam is higher than the values in literature. Although the TEAP TF reports that they ran variations of their models for different foam lifetimes, no details are disclosed.

A very recent study (Lickley et al., 2020) studied the emissions from CFC banks using a probabilistic approach and concluded that bank sizes of CFC-11 and CFC-12 are larger than previously suggested by other scientific assessments. This study shows that the CFC-11 bank could still be well above 1500 kt in 2020.

Our Tier 1 model does not differentiate between different foam types. To make use of the differentiated emission factors, averages were calculated based on the distribution of the total consumption of the foam sector to the different foam types according to the shares stated in FTOC (2006) and as shown in Figure 1. The values for XPS board seem to be those commonly assumed for HFCs, which are released at a much higher rate as the molecules are smaller. The annual release rate for CFC-12 is given as 1.25 % (Obernosterer, 2012), leading to 60 years until all blowing agent is released. The foam types with the largest share of consumption (and bank – compare FTOC, 2010) are PU appliance, PU boardstock, XPS boards, PU continuous and discontinuous panels. Also, a considerable amount of consumption goes into PU flexible foam, where the blowing agent is released at or shortly after the manufacture. That means that the average first-year-release needs to take this into account, when being applied to the overall consumption. Those most prominent foam types in the bank, as marked in grey in Table 6 differ mainly in two ways: The first-year- release and the assumed lifetime. The annual release rate is rather uniform between 0.25 and 0.75 %, only XPS boards have higher rates. The lifetimes differ between foam that is used in construction and those in appliances and other uses such as mattresses and pipe insulation.

The set of global average emission factors is part of Table 7. Since XPS boards is the only foam application where CFC-12 is used, the average emission factors can be separated from CFC-11 and CFC-12 applications.

Figure 1: Global distribution of consumption in the foam sector. Source: FTOC (2006)



3.2 Data sets for recalculation of the global banks model

The gathered data points identified in the literature and from country research are presented in Table 7. A global average was largely deducted from application specific values given by Ashford et al. (2004) and is shown in columns 4 to 6. Country specific values could only be inferred for the lifetime of buildings and appliances and suggest longer lifetimes than used in our model.

Although the Tier 1 model cannot differentiate between the foam applications, it was found useful to consider different emission patterns for insulation foam used in buildings and appliance foam. Other foam types constitute only a small fraction of the total bank. The later sensitivity analysis shows the possible variations in the bank caused by different underlying emission patterns resulting from applied lifetime and emission factors. For the recalculation of the model, the total CFC-11 consumption for foam was attributed to appliance and building applications. 30 % are assumed to have been used for appliance foam, and 70 % into building foam. Other types are neglected and foam types leading to a full immediate release of the blowing agent are assumed to be covered by the “Other category” applied to the total CFC consumption in the original model (15 % for nA5, 25 % for A5 countries).

To improve the modelling of bank and waste emissions, especially when applying longer foam lifetimes, the consumption dataset was extended to reach back to 1960, to the time when large scale CFC consumption started. The back-projection was done on the basis of data presented in the FTOC (2014).

The calculation formula was modified to take into account the building and appliance lifetimes independently from the timespan that the foam is releasing the blowing agent.

Table 7: Assumptions for foam sector bank calculation

	Default values (Gamlen model)	**TEAP 2019**	**Developed countries**	**Developing countries**	**Global average**			**ODS inventories in project partner countries**	**Country research**
					CFC-11 appliances	CFC-11 buildings	CFC-12 XPS board		
EF_{fy}	5-10 %	30 %	5 %	10 %	4 %	14 %	25 %	systematic stock taking was not possible due to lack of data sources	no country specific values
EF_{use}	4.50 %	8 %	2 %	2 %	0.25 %	0.69 %	1.25 %		no country specific values
Lifetime (years)	20	not stated	20	20	25	50	50		average for buildings: 46 years (Austria) average for appliances: 25 years[20] (Germany)
time to total release (years)	20-21	not stated	47.5[21]	45[22]	384	152	60		no country specific values
Blowing agent left when entering the waste stream (% of Initial Charge)	0-5 %	not stated	55 %	50 %	92 %	51 %	12.5 %		no country specific values

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[20] estimated from waste appliances delivered to recycling facilities

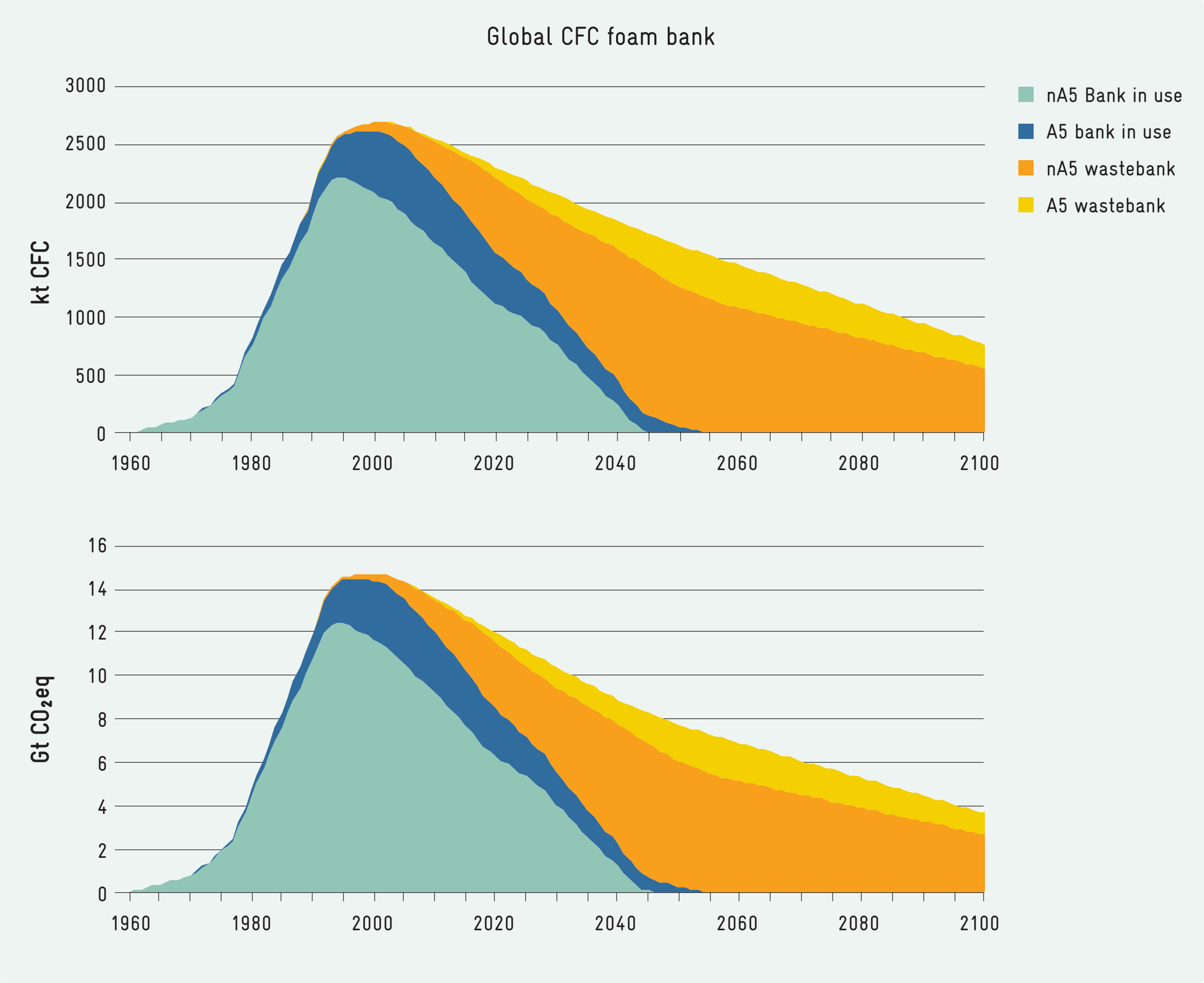
[21] it is assumed that the blowing agent is released or treated, when it enters the waste stream

[22] it is assumed that the blowing agent is released or treated, when it enters the waste stream

4 Results

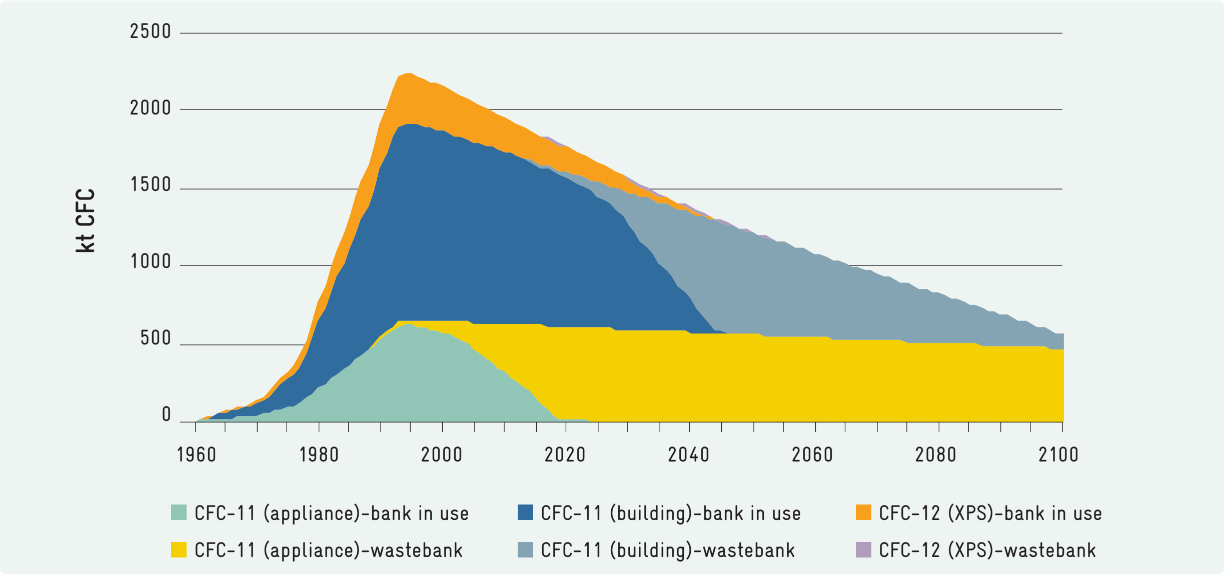
Applying the global average emission patterns shown in Table 7 to the estimated foam consumption results in the bank projection shown in Figure 2. The bank in use includes insulation foam in appliances that are in use and insulation foam in buildings. For the bank contained in the waste, it was assumed that foam is untreated and continues to release the blowing agent at a constant rate. Considering that some efforts are undertaken to recover CFCs, mainly from appliances, the wastebank might be a little overestimated. However, in the case of building foam, little evidence was found that they are recovered prior to demolition, and adequately destroyed. The total foam bank is estimated to be 1500 kilo tonnes CFC in 2020. These are 8.5 Gt of CO_2 equivalents. Currently, proper treatment is performed in very few countries, thus a large part of the CFC bank is prone to be emitted to the atmosphere. The majority of the foam bank is located in developed countries and although decreasing, it is likely that CFCs, equivalent to 6.3 Gt CO_2eq, have not yet entered the waste stream. That means that theoretically they are still reachable for treatment. This is more than the annual GHG emission of the European Union (4.3 Gt CO_2eq in 2016; EEA, 2018). If not treated properly, those amounts will gradually enter the waste stream, releasing the blowing agent either during shredding and/or continuing the annual release when landfilled.

Figure 2: Global CFC Foam banks, shown as amount of CFC (left) and CO_2-equivalents (right)



The majority of the bank in developed countries is located in buildings. With the assumed average building lifetime of 50 years, the demolition waste from buildings with its insulation foam is just about to enter the waste stream, opening a window of opportunity to avoid 870 kilo tonnes of CFC emissions. This is equivalent to 4.5 Gt CO_2eq.

Figure 3: CFC foam bank in developed countries (summed graph)



4.1 Sensitivity Analysis

The aim of the sensitivity analysis is to study the effects of varying the model parameters and to illustrate the interdependencies between them. For the sensitivity analysis, three independent model parameters were varied: the emission factor for emission in the first year (EF_{fy}), the timespan until all blowing agent content is emitted (LT) and the lifetime of the building or appliance after which it reaches its end of life (LT_{build}). Assuming a constant diffusion rate from the foam in use, the emission factor from the foam in use (EF_{use}) is calculated according to the equation below. The foam consumption is kept constant for all variations and equal to the foam consumption developed under our model (see chapter 3.2).

$$EF_{use} = \frac{(1 - EF_{fy})}{LT}$$

EF_{use}	Annual emission from the foam product
EF_{fy}	Emission during the first year after manufacture (incl. emission just after manufacture)
LT	Timespan until no blowing agent is left in the foam product

The parameters are varied one by one within the values given in Table 8, applying the stated intervals. This leads to 198 variations. The development of banks, emission from banks, amounts reaching the waste stream and emission from waste (assuming no destruction) are plotted for each variation.

Table 8: Assumptions for foam sector sensitivity analysis

	Minimum	Maximum	Interval
EF_{fy}	0 %	100 %	20 %
Lifetime	1	200	20 (first interval=19)
EF_{use} (calculated)	0 %	100 %	Not regular
Lifetime of building/appliance	30	100	First interval: 20 Second interval: 50

The amount that is added to the bank of blowing agents is directly depending on the first-year emission factor, which determines the starting amount of the bank. Lower emission rates from the bank lead to higher recoverable amounts when the foam enters the waste stream. The shorter the lifetime of the appliance or building, the higher the recoverable amounts. However, at very low emission rates from the bank, the influence of the lifetime of the appliance or building is low.

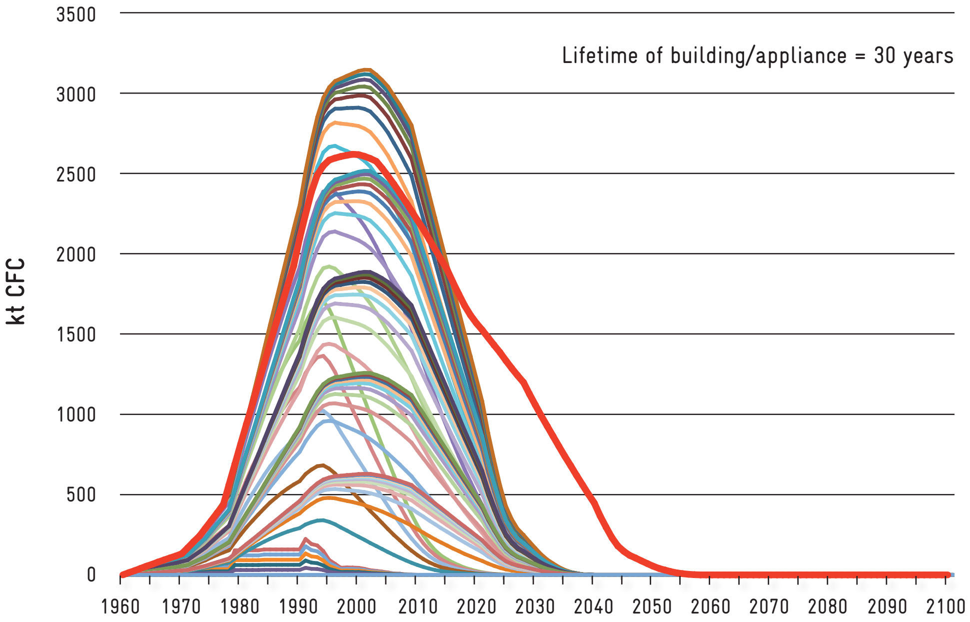
Some of the effects described above and illustrated in Table 9 have opposing effects and the combination of them decides on the resulting bank and their emissions. All variations for bank and amounts present when entering the waste stream are plotted in Figure 4–6. The results are aggregated for CFC-11 and CFC-12 for nA5 as well as A5 countries. Each figure shows the variations of first-year emissions and the timespan until all blowing agent hast left the foam in the absence of treatment.

Table 9: Dependencies and influence of varied model parameters on model results. Reading example: if the time to the total release of the blowing agent is longer, the bank is higher, the amounts when entering the waste streams are higher and the annual bank emissions are lower.

	First year release	Time to total release	Release rate (calculated)	Lifetime of appliance/building
Variation of model parameter	↑	↑	↑	↑
Effect on bank size	↓	↑	↓	↑
Effect on waste amounts	↓	↑	↓	↓
Effect on annual bank emissions	↓	↓	↓	↑

The maximum amount of the bank in each figure results from the variations of EF_{fy}. The lower the first-year emissions, the higher the bank. The bank reaches zero ahead of the appliance/building lifetime, where the timespan to the complete release of the blowing agent is shorter than the appliance/building lifetime. The bold red line shows the model result presented above. Under the assumption that the waste is landfilled without treatment, which is the most common practice, the resulting amount of blowing agent in the waste is shown as wastebank.

Figure 4: Variations of global CFC foam bank (above) and waste bank (below), for 30 years appliance/building lifetime, own elaboration



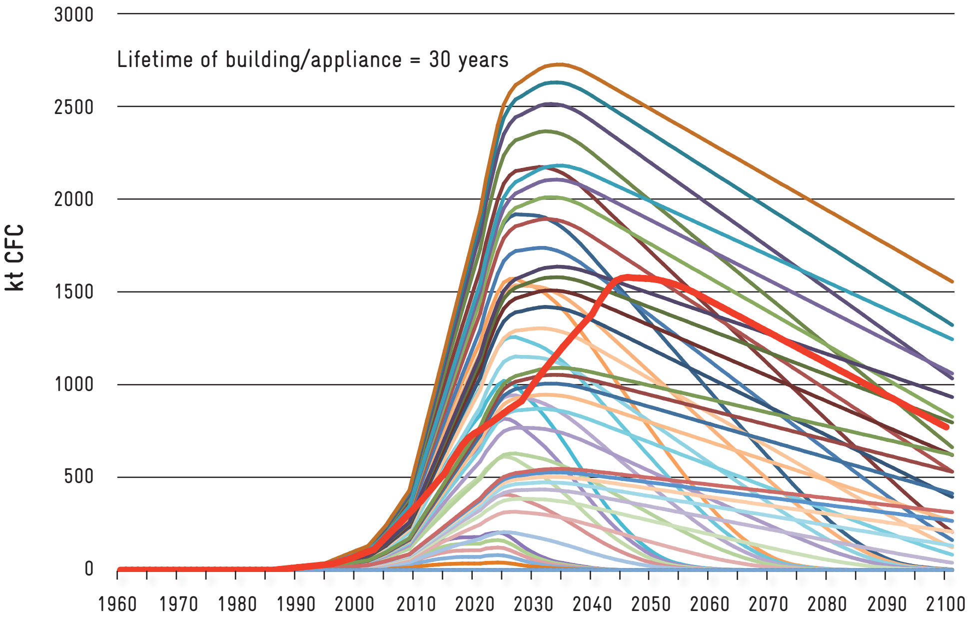
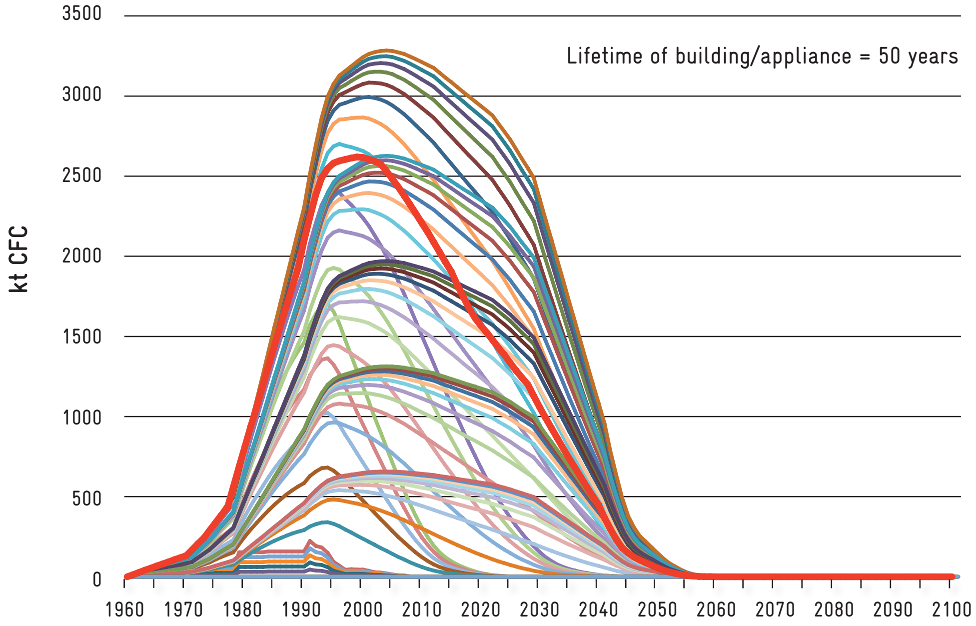


Figure 5: Variations of global CFC foam bank (above) and waste bank (below), for 50 years appliance/building lifetime, own elaboration



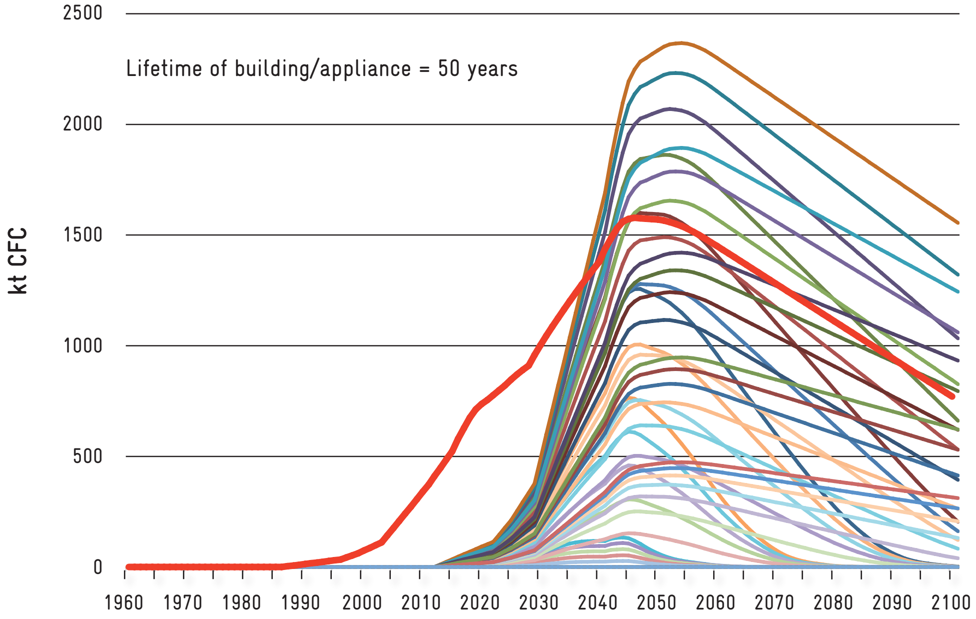
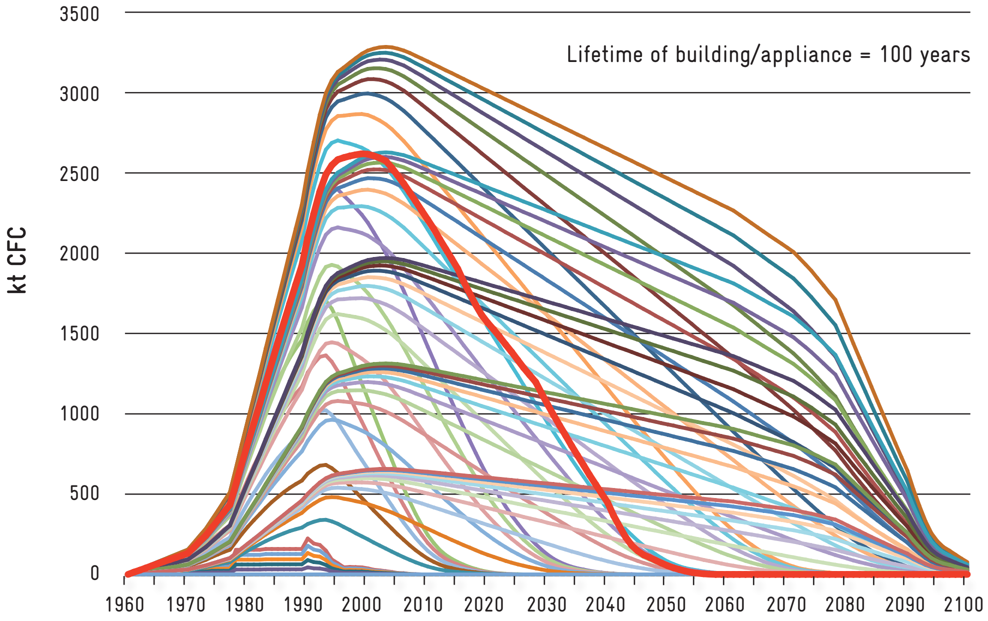
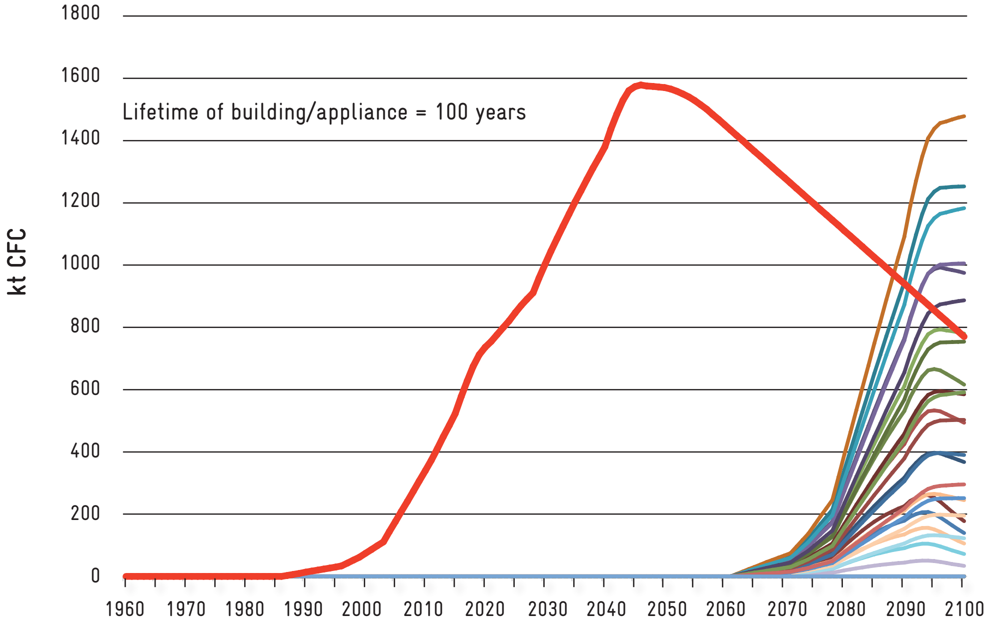


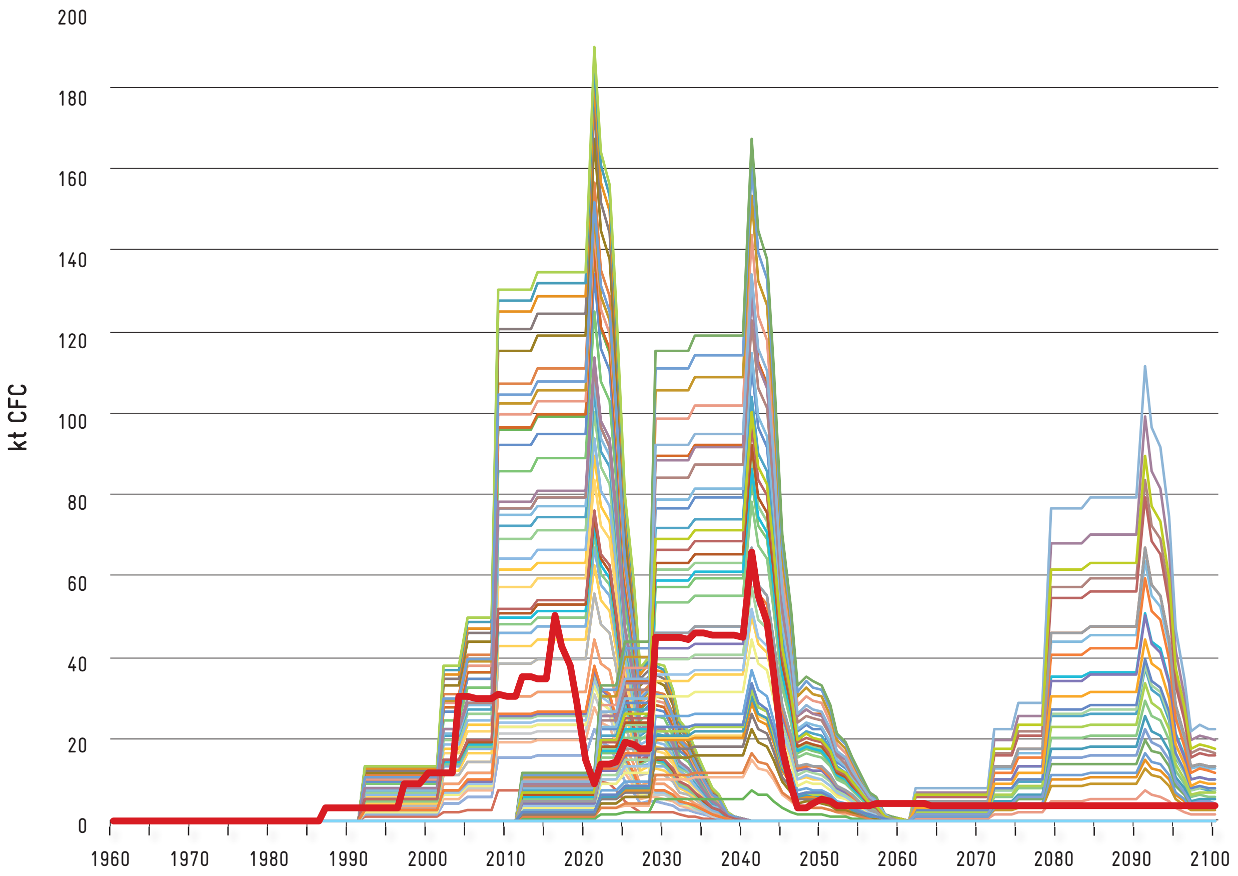
Figure 6: Variations of global CFC foam bank (above) and waste bank (below), for 100 years appliance/building lifetime, own elaboration





The resulting amounts available for treatment do vary considerably in two ways: The amount and the time when the amount reaches the waste stream. Figure 7 shows these variations. The effect of EF_{fy} variation on the amount of CFC entering the waste stream and the effect of EF_{build} variations on the time when the CFC enters the waste stream can clearly be identified. That means that given the country evidence on longer lifetimes, it is likely that CFC amounts available for recovery are still substantial. The bold red line shows again the model result with the previously assumed parameters.

Figure 7: Variations of global CFC from foam applications entering the waste stream



5 Conclusions

The size of CFC banks, the resulting emissions and adequate action to mitigate those emissions is an ongoing debate. This paper contributes to this debate by shedding light on the mechanics of foam banks models, ample country cases and offering a refined global foam bank model. The sensitivity analysis shows that the total amount of CFC emissions in the model runs does not change, as it is equal to the given consumption in the past. However, the timing of emissions is subject to modelling parameters such as emission factors during manufacture and use, as well as the lifetime of appliance and buildings. The modelled emissions directly determine the amount of CFC still present when the appliance or the insulation foam enters the waste stream. The evidence gathered from country studies implies that lifetimes of appliances and buildings are longer than assumed in previous models (Ashford et al., 2004; FTOC, 2006, 2010, 2014; GIZ 2018). Consequently, more CFCs need to be recovered than previously estimated and a more detailed investigation on country-level is needed on CFC-11 and CFC-12 foam banks. The nationally gathered data can be collected in a global registry for CFC and HCFC banks and provide a sound basis for decision makers on how to tackle the estimated 1500 kt of CFC contained in foams in use, which is equivalent to 8.5 Gt of CO_2. For comparison, the total annual greenhouse gas emission of the European Union is 4.3 Gt CO_2eq (EEA (2018).

For appliances, the example of two member states of the European Union has demonstrated that recycling, including the recovery and destruction of the insulation foam, can be organized. A large percentage of the discarded refrigerators are recycled professionally, thereby reducing CFC emissions.

For insulation foams in buildings, some European Union countries e.g. Germany and Austria made it obligatory to remove and treat insulation foam containing CFC, HCFC or HFC prior to the demolition of a building, and thus achieved CFC emission reduction.

6

Outlook

The given examples show that the actual practicing of recycling depends on the engagement of the government to make recycling obligatory. CFC containing foams can generally be destroyed by thermal destruction in municipal waste incineration facilities or hazardous waste incineration, as well as cement kilns (GIZ, 2019). Required destruction capacities are low compared to national waste streams and research on additional costs for such a procedure are shown to be less than 1% of total renovation or destruction costs (Obernosterer et al., 2007). Therefore, the technical infrastructure for destruction is usually available. The current reluctance often encountered in recyclers and operators of cement kilns to accept CFC foams can be overcome by creating a market and regular waste streams by imposing a regulation.

Given the aggravating climate crisis, more efforts to further quantify and recover CFCs from foams should have highest priority.

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