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Banked CFC-11 contributes to an unforeseen emission rise and sets back progress towards carbon neutrality

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Table S1 Literature review for global and regional CFC-11 emissions using bottom-up and top-down estimating models

Literature	Timeframe	Geographic	Method	Data sources	CFC-11 emission note
Global					
This study	1950–2100	Global and regional	Bottom-up	AFEAS (2003), McCulloch et al. (2001), and TEAP (2006; 2019)	Lifetime and end-of-life handling of durable foam products significantly impact emission.
Gamlen et al., 1986	1960–1984	Global	Bottom-up	AFEAS (2003) and assumptions regarding production excluded by AFEAS	The estimated production loss associated with closed-cell foam products is 10%, followed by an annual loss of 4.5 % over the subsequent 20 years.
Cunnold et al., 1994	1978–1991	Global	Top-down & bottom-up	Atmospheric measurements, AFEAS (2003) and UNEP (2024)	The top-down and bottom-up estimates of CFC-11 emissions can be reconciled, with the estimated lifetimes of CFC-11 being 44 (34–61) years.
McCulloch et al, 1994	1986	Global and national	Bottom-up	Consumption data from national reports to the UNEP (2024)	A correlation has been established between Gross Domestic Product (GDP) and total CFC consumption.
McCulloch et al., 2001	1950–1999	Global	Bottom-up	AFEAS (2003), UNEP (2024), and Gamlen et al. (1986)	A new emission function has been necessitated for closed-cell foams since the early 1990s in order to align with CFC-11 atmospheric concentrations.
TEAP, 2006	1990–2004	Global	Bottom-up, top-down	AFEAS (2003), UNEP (2024), and atmospheric measurements	Top-down emissions of CFC-11 exceed those estimated from bottom-up approaches.
Montzka et al., 2018	1994–2016	Global	Top-down	Atmospheric measurements	An increase in CFC-11 emissions of 13 ± 5 Gt/yr has been observed since 2012.
TEAP, 2019	1932–2017	Global	Bottom-up	AFEAS (2003), UNEP (2024) and production estimates for Russia in 1968–1989	Annual CFC-11 production of 40–70 kt is required from 2012 onwards to account for the observed unexpected emissions.
Laube et al., 2020	2009–2018	Global	Top-down	Sampling surveys conducted at altitudes exceeding those of aircraft	Dynamical changes in the stratosphere may explain the observed alterations in tropospheric CFC-11 emissions following 2013, albeit with a considerable degree of uncertainty.
Montzka et al., 2021	2000–2019	Global	Top-down	Atmospheric measurements	The 2019 estimate of 52 ± 10 Gt/yr is comparable to the mean value observed in 2008−2012.

Literature	Timeframe	Geographic	Method	Data sources	CFC-11 emission note
Lickley et al., 2021	1960–2020	Global	Bayesian	AFEAS (2003) and UNEP (2024)	New and unexpected emissions of CFC-11 during 2014–2016 were estimated to be 23.2 Gg/yr.
TEAP, 2021	1940–2019	Global	Bottom-up	Same as TEAP (2019)	The estimated cumulative unreported CFC-11 production is 320-700 kt in the period 2007–2019.
Hu et al., 2022	2012–2017	Global and regional	Top-down	Aircraft sampling surveys and atmospheric measurements	Asia accounted for the largest proportion of global CFC-11 emissions in 2009–2011 (43%) and 2016–2018 (57%), representing 86% (59–115%) of the overall rise in CFC-11 emissions between these two periods.
North America (The U.S. and Canada)					
Hurst et al. 2006	2003	Continental United States (U.S.) and Canada	Top-down	In site measurements within and above the planetary boundary layer over the U.S. and Canada, and emission ratios to CO	8±3 Gg/yr of CFC-11 emissions for the region in 2003
Millet et al., 2009	2004–2006	The U.S. and Mexico	Top-down	Aircraft sampling measurements, and emission ratios to CO	11 (7–14) Gg/yr of CFC-11 emissions for the U.S. during 2004–2006
Miller et al., 2012	2004–2009	The U.S.	Top-down	Aircraft sampling measurements, and emission ratios to CO_2	10 (4–61) Gg/yr of CFC-11 emissions for the period 2004–2009
Gallagher et al., 2014	2008	California, U.S.	Bottom-up	Industry surveys and analysis of foam usage in California	0.035 kg/capita of CFC-11 emissions in 2008
Hu et al. 2017	2008–2014	The U.S.	Top-down	Measurements in discrete air samples from the U.S. and remote sites around the globe, and a Bayesian inversion model	CFC-11 emissions changed from 8.0 ± 1.4 Gg/yr in 2008 to 4.5 ± 0.7 Gg/yr in 2014
U.S. EPA, 2024	1990–2022	The U.S.	Bottom-up	Sales categorized by end-use applications	CFC-11 emissions declined from 29 (27–54) kt/yr in 1990 to 5 kt/yr by 2022.
This study	1990–2100	The U.S.	Bottom-up	Sales categorized by end-use applications	CFC-11 emissions decreased from 40 (38–44) kt/yr in 1990 to 9 (5–12) kt/yr by 2022
European non-A5					

Literature	Timeframe	Geographic	Method	Data sources	CFC-11 emission note
McCulloch and Midgley, 1998	1986–1996	Europe Union	Bottom-up	Sales categorized by end-use applications	CFC-11 emissions decreased from 125 kt/yr in 1986 to 44 kt/yr in 1996
Derwent et al., 1998	1987–1996	Europe	Top-down	Atmospheric measurements at Mace Head, using a simple climatological long-range transport and NAME models	CFC-11 emissions decreased from 170 kt/yr in 1987 to 13.7 kt/yr by 1996
Ryall et al., 2001	1995–1998	Europe	Top-down	Atmospheric measurements at Mace Head, using the dispersion NAME inversion model	8.5 (8.2–8.6) kt/yr of CFC-11 emissions during 1995–1998
Buchmann et al., 2003	1994–1999, and 2002	Switzerland	Top-down	Atmospheric measurements at Dübendorf, combining information about the night-time boundary layer height	CFC-11 emissions in 2002 have decreased by 82% compared to 1993; however, measurements in 2002 still revealed the presence of significant peak events.
Manning et al., 2003	1995–2000	Western Europe (Ireland, UK, France, Germany, Denmark, and Benelux[#])	Top-down	Atmospheric measurements at Mace Head, using the dispersion NAME inversion model	8.9 (8.5–9.6) kt/yr of CFC-11 emissions for 1995–2000
Stemmler et al., 2007	2000–2004	Central Europe (Germany, France, Italy, Switzerland, and Benelux[#])	Top-down	Atmospheric measurements at Jungfraujoch, and emission ratios to CO	2.4 (1.9–2.7) kt of CFC-11 emissions in 2000, rising to 4.7 (4–4.8) kt by 2003, followed by 4.1 (4.1–4.7) kt/yr in 2004
Keller et al., 2012	2009	European central west, central north, northwest, central south, southeast, northeast, east, and southwest[*].	Top-down	Atmospheric measurements at K-Puszta, Jungfraujoch, Mace Head and Monte Cimone, and the FLEXPART inversion model	Total CFC-11 emissions of 4.2 (2.9–5.4) Gg/yr, and the highest levels observed in central west, central north, and central south Europe[*].

Literature	Timeframe	Geographic	Method	Data sources	CFC-11 emission note
Manning et al., 2022	1990–2020	UK	Top-down	Atmospheric measurements at Mace Head, and four tall tower stations including Ridge Hill, Tacolneston, Bilsdale, and Heathfield, using the InTEM model	CFC-11 emissions varied from 6 ± 0.9 Gg/yr in 1990 to 0.16 ± 0.04 Gg/yr in 2020, with an increase trend observed from 0.28 ± 0.08 Gg/yr to 0.41 ± 0.1 Gg/yr during the period of 2014–2017.
Rust et al., 2022	2019–2020	Switzerland	Top-down	Atmospheric measurements at Beromünster, Jungfraujoch, Mace Head, and Tacolneston, using emission ratios to CO and also a FLEXPART inversion model	65 ± 24 tonnes/yr of CFC-11 emissions for 2019–2020
Redington et al., 2023	2008–2021	Western Europe (Ireland, the UK, France, Italy, Germany, Benelux#, Switzerland, Austria and Denmark)	Top-down	Atmospheric measurements at Mace Head, Jungfraujoch, Monte Cimone and Tacolneston, using four inversion models	CFC-11 emissions averaged 2.4 ± 0.4 Gg/yr in 2008–2021, with a bank release rate of 3.4% (2.6%–4.5%). The region including northern France and the Benelux# showed consistently elevated emissions of CFC-11 compared with the surrounding regions.
This study	1986–2100	European non-A5	Bottom-up	Sales categorized by end-use applications	CFC-11 emissions declined from 160 (157–165) kt/yr in 1986 to 11 (6–17) kt/yr by 2022
Other non-A5					
Dunse et al., 2005	1995–2000	Melbourne, Australia	Top-down	Atmospheric measurements at Cape Grim, and emission ratios to CO	CFC-11 emissions fluctuated between 0.032±0.01 and 0.057±0.01 kt/yr, with no obvious decline observed.
Dunse et al., 2019	1995–2017	Australia	Top-down	Atmospheric measurements at Cape Grim and Aspendale, using emission ratios to CO and inversion model	CFC-11 emissions rose from 462 tonnes (t) in 2003 to 736 t in 2007, with an average of 460 t from 1996 to 2017

Literature	Timeframe	Geographic	Method	Data sources	CFC-11 emission note
Fraser et al., 2020	1960–2017	Australia	Top-down	Atmospheric measurements at Cape Grim and Aspendale, emission ratios to CO and inversion model; national CFC consumption estimates for absent measurements	Since 2010, CFC-11 annual emissions have been approximately constant at 0.32 ± 0.04 Gg/yr.
This study	1995–2100	Other non-A5 parties	Bottom-up	Sales categorized by end-use applications	CFC-11 emissions decreased from 0.8 (0.6–1.1) kt/yr in 1995 to 0.3 (0.1–0.5) kt/yr by 2022
Japan					
Palmer et al., 2003	2001	Eastern Asian (China, Japan, and Korea)	Top-down	Aircraft sampling measurements, and emission ratios to CO	2.3 ± 0.6 Gg/yr of CFC-11 emissions for Japan in 2001
Yokouchi et al., 2005	2001–2003	Japan	Top-down	Aircraft monitoring, and emission ratios to HCFC-22	1.6±0.1 Gg/yr of CFC-11 emissions for Japan during 2001–2003
Rigby et al., 2019	2008–2017	western Japan, etc.	Top-down	CFC-11 atmospheric observations in Gosan, South Korea, and Hateruma, Japan	Comparatively small CFC-11 emissions, approximately at 0–2 Gg/yr
Japan METI, 2023	2001–2022	Japan	Bottom-up	Sales categorized by end-use applications	CFC-11 emissions decreased from 2.3 kt/yr in 2001 to 0.5 kt/yr in 2009, subsequently rising to 1.3 kt/yr in 2010, before declining again to 0.7 kt/yr by 2022.
This study	2001–2100	Japan	Bottom-up	Sales categorized by end-use applications	CFC-11 emissions declined from 4.6 (2.4–5.8) kt/yr in 2001 to 0.7 (0.4–1.0) kt/yr by 2022
China					
Palmer et al., 2003	2001	Eastern Asian (China, Japan, and Korea)	Top-down	Aircraft sampling measurements, and emission ratios to CO	22.3 ± 5.8 Gg/yr of CFC-11 emissions for China in 2001
Vollmer et al., 2009	2006–2008	China	Top-down	Atmospheric measurements at Shangdianzi, and FLEXPART inversion model	33 (26 – 43) Gg/yr of CFC-11 emissions in China during 2006–2008

Literature	Timeframe	Geographic	Method	Data sources	CFC-11 emission note
Wan et al., 2009	1995–2024	China	Bottom-up	Sales categorized by end-use applications	CFC-11 emissions rose from 16 kt/yr in 1995 to 29 kt/yr in 1999, subsequently declined to 0 kt/yr by 2022
Wang et al., 2010	1978–2037	China	Bottom-up	Sales categorized by end-use applications	CFC-11 emissions rose from 0.2 kt/yr in 1980 to 17.5 kt/yr in 2004, subsequently decreased to 0 kt/yr in 2028
Li et al., 2011	2008	Eastern Asian (China, Japan, and Korea)	Top-down	Atmospheric measurements at Gosan, and emission ratios to HCFC-22, or HFC-134a	11 (9–15) Gg/yr of CFC-11 emissions for China in 2008
An et al., 2012	2009	China	Top-down	Atmospheric measurements at Shangdianzi, and FLEXPART inversion model	15.8 ± 7.2 Gg/yr of CFC-11 emissions in 2009
Fang et al., 2018	1980–2050	China	Bottom-up	Sales categorized by end-use applications	CFC-11 emissions rose from 1.7 kt/yr in 1980 to 24.1 kt/yr in 1999, subsequently decreased to 0 kt/yr in 2028
Rigby et al., 2019	2008–2017	Eastern China, etc.	Top-down	CFC-11 atmospheric observations in Gosan, South Korea, and Hateruma, Japan	The mean emissions of CFC-11 in eastern China were 6.4 ± 1.2 Gg/yr in 2008–2012 and 13.4 ± 1.7 Gg/yr during 2014–2017
Adcock et al., 2020	2014–2018	Eastern China	Top-down	Air samples collected in Taiwan, using emission ratios to other compounds	19 ± 5 Gg/yr of CFC-11 emissions during 2014–2018
Huang et al., 2021	2012−2018	Eastern China	Top-down	Air samples collected in Shandong, using emission ratios to other compounds	CFC-11 emissions ranged from 12.0 ± 1.6 Gg/yr to 20.8 ± 3.9 Gg/yr between 2014 and 2017−2018
Park et al., 2021	2008–2019	Eastern China	Top-down	CFC-11 atmospheric observations in Gosan, South Korea, and Hateruma, Japan	5.0 ± 1.0 Gg/yr of CFC-11 emissions in 2019, returning to pre-2013 levels
Yi et al., 2021	2009–2019	China	Top-down	Atmospheric sampling measurements at Beijing, Hangzhou, Guangzhou, Lanzhou and Chengdu, and emission ratios to HCFC-22	CFC-11 emissions increased steadily from 8.3 ± 1.6 Gg/yr in 2009, peaking at 13.9 ± 2.4 Gg/yr in 2017 then declined to 10.9 ± 1.7 Gg/yr in 2019, with a mean value of 11.9 Gg/yr during 2009–2019.
This study	1980–2100	China	Bottom-up	Sales categorized by end-use applications	Average emissions of CFC-11 rose from 8 (4–13) kt/yr in 2008–2012 to 11 (5–13) kt/yr during 2014–2018.

Literature	Timeframe	Geographic	Method	Data sources	CFC-11 emission note
Other A5					
Palmer et al., 2003	2001	Eastern Asian (China, Japan, and Korea)	Top-down	Aircraft sampling measurements, and emission ratios to CO	2.9 ± 1.0 Gg/yr of CFC-11 emissions for Korea in 2001
Rigby et al., 2019	2008–2017	South Korea, etc.	Top-down	CFC-11 atmospheric observations in Gosan, South Korea, and Hateruma, Japan	Comparatively small CFC-11 emissions, approximately at 0–2 Gg/yr
Millet et al., 2009	2004–2006	Mexico	Top-down	Aircraft measurements, and emission ratios to CO	5.1 (2.7–8.8) Gg/yr of CFC-11 emissions for Mexico in 2006
Say et al., 2019	2016	India	Top-down	Aircraft sampling measurements, and NAME inversion model	1.7 (0.8–3.1) Gg/yr of CFC-11 emissions in 2016
This study	2010–2100	Other A5 parties	Bottom-up	Sales categorized by end-use applications	Average emissions of CFC-11 remained at 17 (10–20) kt/yr during 2010–2022

Abbreviation: fluorotrichloromethane (CFC-11), Chemical statistics from Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), United Nations Environmental Programme (UNEP), end-of-life (EoL), gigagrams per year (Gg/yr), kilotonnes (kt), Montreal Protocol on Substances that Deplete the Ozone Layer UNEP Technology and Economic Assessment Panel (TEAP), Numerical Atmospheric Dispersion Modeling Environment (NAME), Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT), Lagrangian Particle Dispersion Model (LPDM), Inversion Technique for Emission Modelling (InTEM).

[#] Benelux: The Netherlands, Belgium, and Luxembourg

*European central west (Belgium, France, and Luxembourg), central north (Denmark, Germany, and The Netherlands), northwest (Ireland and the United Kingdom), central south (Austria, Italy, and Switzerland), southeast (Albania, Bulgaria, parts of Greece, Hungary, Romania, and former Yugoslavia), northeast (Czech Republic, Poland, and Slovakia), east (Belarus, Latvia, Lithuania, Moldova, and the western part of the Ukraine), and southwest (Portugal and Spain).

Countries are classified into non-article 5 (non-A5) and article 5 (A5) parties under the Montreal Protocol. In this study, non-A5 parties include North America (including the United States (U.S.) and Canada), European nations categorized as non-A5 (European non-A5), Japan and other non-A5 parties; while A5 parties consist of China and other countries recognized as A5 under the Montreal Protocol (other A5).

Table S2 Closed-cell foam product average lifetime from literature review

Breakdown of closed-cell foam	McCulloch et al., 2001	FTOC, 2002	IPCC, 2006	TEAP, 2021	U.S. EPA, 2024
Domestic Refrigeration	15	15	15	25	14
Commercial Refrigeration & other Appliances	15	15	15	15	10
Refrigerated Containers	15	15	15	7	12
PU Boardstock	60	50	25	50	40
PU Continuous Panels	25	50	50	75	75
PU Discontinuous Panels	25	50	50	75	75
PU Spray Foam	50	50	50	50	50
PU Block & Pipe	15	15	15	15	15
PU Pipe in Pipe	15	50	50	15	15
PU Block Foam Slab	15	15	15	15	15

PU (polyurethane). The breakdown of closed-cell foam is derived from Technology and Economic Assessment Panel (TEAP, 2019; 2021). In this study, these breakdowns have been reorganized, with a detailed description provided in S1.2.

Table S3 Surveys on the lifespan of closed-cell foam product applications

Literature	Object	Timeframe	Geographic	Data	Simulation model	Lifespan change
Tasaki et al., 2001	Refrigerator	1991–1998	Japan	Quantity of goods delivered and in possession	Weibull distribution	Decreased from 12.2 years in 1991 to 11.5 years in 1998.
Tsutsumi and Komatsu, 2004	Wooden houses	1980–2000	Osaka, Japan	Statistics on new residential construction and housing stock	Normal distribution, Lognormal distribution, Weibull distribution	28.6–47.2 years in Central district, 31.2–53.1 years in Higashidogawa, and 32.4–48.9 years in Hirakata, varying by building vintage.
Omi and Kurita, 2010	Building by main frame types	1987, 1997, 2005 surveys	Japan	Statistics on new residential construction and housing stock	Weibull distribution	30.5–53.8 years, 34.3–47.2 years, and 43.1–55.8 years in the 1987, 1997 and 2005 surveys, varying by building function types.
Aktas and Bilec, 2012	Residential building	1997–2009	The U.S.	Over 3,700 data points	Weibull distribution	50–61 years, varying by building vintage.
Cao et al., 2019	Building	1950–2015	China	Over 4000 field survey samples	Weibull distribution	The average lifespan decreased from 39.4 years in 1950–1969 to 25.3 years in the 1980s, followed by a subsequent increase to 26.6 years in the 1990s and further rising to 33.8 years in 2000–2015, with variations based on building vintage.
Huuhka and Lahdensivu, 2014	Building by function	2000–2012	Finland	50,818 cases of demolition or destruction	Subtracting the construction year from the demolition year.	32–64 years, with most falling within the range of 32 to 47 years, varying by building function types
Ji et al., 2021	Building by main frame types	1950s–2010s	South Korea	971,514 cases of demolition	Machine learning	10.7–52.6 years, with the majority falling below 32 years, varying by region and main frame type.
Andersen and Negendahl, 2023	Building by function	2007–2020	Denmark	124,096 cases of demolition	Subtracting the construction year from the demolition year.	40–80 years for non-resident buildings and 58–145 years for resident buildings built during 1960–1999, varying by functions.

Building by function covers residential buildings (such as detached houses, apartment buildings, dormitories, etc.) and non-residential buildings (such as commercial and office buildings, public buildings, industrial buildings, retail, shops and warehouses, hotels & restaurants, etc.).

The main frame types of building include wooden, block, brick, reinforced concrete, masonry, steel pipe, light gauge steel, steel, etc.

Table S4 Research on end-of-life (EoL) handling and post-life of closed-cell foam products

Literature	Object	Timeframe	Place of origin	Sampling site	EoL related process
Shredding process related					
Kjeldsen and Jensen, 2001	Three refrigerators	Manufactured in 1984 and 1986	Denmark and Rumania	Laboratory experiments	a) Up to 10% of the CFC-11 was released within a few weeks for 2cm cubes; b) The release of 50% CFC ranges from 1.35 to 135 years for particles in size of 0.5–5 cm.
Kjeldsen and Scheutz, 2003	An old refrigerator	Not clear	Not clear	Laboratory experiments	a) Release patterns are highly dependent on how particle sizes, such as instantaneous release (in minutes) of 40% and short term release (in weeks) of 60% of the BA for shredded particles less than 4 mm; b) The instantaneous releases decreased from 35–40% of BA for shredded particle size of 2–4 mm to ~10% for particle size of 16–32 mm; c) An estimated release rate of 18–24% of BA for particles in the full-scale shredder, mainly within the size of 4–32 mm.
Scheutz et al., 2007	Eight refrigerators	Manufactured before 1993	The U.S.	Laboratory experiments and shredder facilities	a) Loss of BA by the shredding process for particles less than 8 mm was in the range of 57–61.3%. b) An average of 24.2%±7.5% of BA can be released by the shredding process.
Liu et al., 2011	Two refrigerators	Manufactured during 1980s-1990s	China	Laboratory experiments	The instantaneous releases were 41%, 65%, 71 and 75% for particle sizes of <8 mm, <4 mm, <1 mm and <0.5 mm.
Landfilling related					
Bogner et al., 2003	Emissions from landfill site	2001	France	Static flux chambers at landfill site	CFC-11 emissions rate at 5.2×10^{-7} – 7.9×10^{-5} g m^{-2} day^{-1}; CFC-11 was not degraded in the presence of CH_4 and O_2.
Barlaz et al., 2004	Emissions from landfill site	2002-2003	The U.S.	Static chambers at landfill site	CFC-11 emission rate at -1.84×10^{-4} – 2.08×10^{-5} g m^{-2} day^{-1}
Archbold et al., 2012	Emissions from landfill site	2004	Northern Ireland	Flux chambers at landfill site	CFC-11 emission rate at $3.31\times10^{-5} \pm 2.65\times10^{-5}$ / $1.70\times10^{-5} \pm 3.30\times10^{-5}$ g m^{-2} day^{-1}

Yeşiller et al., 2018	Emissions from landfill site	2014	California, U.S.	Large-scale static chambers at landfill site	CFC-11 emission rate varied over 7 orders of magnitude across the cover types in a given season, and wet: 10^{-8}–10^{-1} g m^{-2} day^{-1}; dry: 10^{-9}–10^{-2} g m^{-2} day^{-1}
Other process					
Kjeldsen and Jensen, 2001	Three refrigerators	Manufactured at 1984 and 1986	Denmark and Rumania	Laboratory experiments	Around 60 % of CFC-11 can be released by compression process
Kjeldsen and Scheutz, 2003	An old refrigerator	Not clear	Not clear	Laboratory experiments	70–77% of CFC-11 can be released by compression test
Scheutz et al., 2007	Eight refrigerators	Manufactured before 1993	The U.S.	PUR samples of thickness⩽1 cm in a closed bottle were incubated in an oven for 48 hour at 140 °C.	Around 85 % of CFC-11 can be released by first heating step

Blowing agent (BA), polyurethane rigid (PUR)

Table S5 Geographic areas classification in this study

Region	**Country composition** (UNEP, 2025)	Note
North America	United States of America (U.S.), Canada	non-A5
European non-A5	Andorra, Austria, Belarus, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, European Union, Finland, France, Germany, Greece, Holy See, Hungary, Iceland, Ireland, Italy, Latvia, Lichtenstein, Lithuania, Luxembourg, Malta, Monaco, Netherlands, Norway, Poland, Portugal, Romania, Russian Federation, San Marino, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom of Great Britain and Northern Ireland.	non-A5
Japan	Japan	non-A5
Other non-A5	Australia, New Zealand, Azerbaijan, Israel, Kazakhstan, Tajikistan, Uzbekistan.	non-A5
China	China	A5
Other A5	Afghanistan, Albania, Algeria, Angola, Antigua and Barbuda, Argentina, Armenia, Bahamas, Bahrain, Bangladesh, Barbados, Belize, Benin, Bhutan, Bolivia (Plurinational State of), Bosnia and Herzegovina, Botswana, Brazil, Brunei Darussalam, Burkina Faso, Burundi, Cabo Verde, Cambodia, Cameroon, Central African Republic, Chad, Chile, Colombia, Comoros, Congo, Cook Islands, Costa Rica, Cuba, Côte d'Ivoire, Democratic People's Republic of Korea, Democratic Republic of the Congo, Djibouti, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Eritrea, Eswatini (the Kingdom of), Ethiopia, Fiji, Gabon, Gambia, Georgia, Ghana, Grenada, Guatemala, Guinea, Guinea Bissau, Guyana, Haiti, Honduras, India, Indonesia, Iran (Islamic Republic of), Iraq, Jamaica, Jordan, Kenya, Kiribati, Kuwait, Kyrgyzstan, Lao People's Democratic Republic, Lebanon, Lesotho, Liberia, Libya, Madagascar, Malawi, Malaysia, Maldives, Mali, Marshall Islands, Mauritania, Mauritius, Mexico, Micronesia (Federated States of), Mongolia, Montenegro, Morocco, Mozambique, Myanmar, Namibia, Nauru, Nepal, Nicaragua, Niger, Nigeria, Niue, North Macedonia, Oman, Pakistan, Palau, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Qatar, Republic of Korea, Republic of Moldova, Rwanda, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Samoa, Sao Tome and Principe, Saudi Arabia, Senegal, Serbia, Seychelles, Sierra Leone, Singapore, Solomon Islands, Somalia, South Africa, South Sudan, Sri Lanka, State of Palestine*, Sudan, Suriname, Syrian Arab Republic, Thailand, Timor-Leste, Togo, Tonga, Trinidad and Tobago, Tunisia, Turkey, Turkmenistan, Tuvalu, Uganda, United Arab Emirates, United Republic of Tanzania, Uruguay, Vanuatu, Venezuela (Bolivarian Republic of), Viet Nam, Yemen, Zambia, Zimbabwe	A5

A5 means “article 5 parties” of the Montreal Protocol, and non-A5 means “non-article 5 parties” of the Montreal Protocol. In this study, non-A5 parties include North America (including the United States (U.S.) and Canada), European nations categorized as non-A5 (European non-A5), Japan and other non-A5 parties; while A5 parties consist of China and other countries recognized as A5 under the Montreal Protocol (other A5).

State of Palestine*: temporary classification as Article 5 party pending a decision of the Parties for permanent classification.

S1. CFC-11 Database

S1.1 Global consumption data of CFC-11

Estimation of global fluorotrichloromethane (CFC-11) emissions necessitates a comprehensive dataset encompassing production and consumption data for each end-use application. The Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) database (AFEAS, 2003), which compiles industry-reported quantities, typically serves as the foundation for such datasets. However, this database has not included data for China, the Czech Republic, India, Korea, Taiwan, Romania and Russia (McCulloch et al., 2001). To bridge this gap, previous studies have sought to integrate disparate time-series data sources to enhance the global CFC-11 database (McCulloch et al., 2001; UNEP, 2006; TEAP, 2019; 2021). In this study, we have adopted the maximum values obtained from previous datasets (AFEAS, 2003; McCulloch et al., 2001; TEAP, 2006; 2021), resulting in a total global estimate of CFC-11 production amounting to 10,166 kilotons (kt) for the period spanning 1950–2014 (Figure S1). This quantity is marginally higher than the estimate of 10,100 kt during the same period by the Technology and Economic Assessment Panel (TEAP) in 2019, reflecting a minor discrepancy of approximately 1.5%.

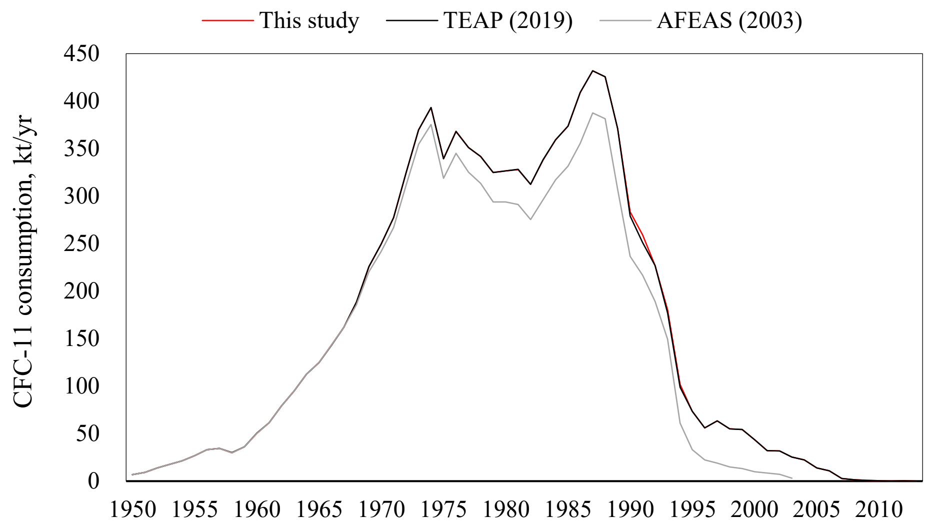

Figure S1 Global CFC-11 consumption comparative analysis. The CFC-11 dataset used in this study is derived from the highest reported values found in previous studies. This dataset is compared with data obtained from the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) and the Technology and Economic Assessment Panel (TEAP), while excluding any unreported production.

S1.2 Sub-sectors of CFC-11 in closed-cell foam

CFC-11 was extensively used in the production of closed-cell foams across a multitude of industrial sectors. Historical data from the Report of the Flexible and Rigid Foams Technical Options Committee (FTCO) categorized foams containing Chlorofluorocarbons (CFCs) into several types, including polyurethane (PU), phenolic, extruded polystyrene (XPS), polyolefin (Table S6). Among these foam types, open cell foam typically consisted of PU flexible (PUF) and PU rigid (PUR) packaging foams, while closed-cell foam comprised rigid insulating foams and other variants of rigid packaging foams. Rigid insulation foams, such as PUR and phenolic foams, were commonly formulated with CFC-11. In contrast, XPS boardstock was typically produced using dichlorodifluoromethane (CFC-12). Additional rigid packaging foams, such as XPS sheets and polyolefin products, were known to incorporate a mix of CFC-11, CFC-12, and other CFCs, reflecting the diverse applications of CFCs within the foam industry.

Table S6 Types and major applications of foam products contained CFCs

Types	Major uses		Products	CFC type
Open cell foam	PUF		Furniture cushions, seat cushion, molded furniture, etc	CFC-11
	PUR packaging		packaging	CFC-11
Closed cell foam	PUR	Appliance	Insulation for domestic refrigerators and freezers, water heaters, commercial refrigeration units, etc.	CFC-11
		Boardstock/lamination	Building Insulation	CFC-11
		Panels		CFC-11
		Spray	Building and tank insulation	CFC-11
		Slabblock and others	Building and pipe insulation, etc.	CFC-11
	Phenolic		Building Insulation	CFC-11
	XPS boardstock		Building Insulation	CFC-12
	Rigid packaging	XPS sheet	Stock food trays, carry-out containers, egg cartons, etc.	CFC-12
		Polyolefin	Cushioning, packaging, flotation devices, etc.	CFC-11, CFC-12, CFC-114

Note: PU (polyurethane), PUF (polyurethane flexible), PUR (polyurethane rigid), XPS (extruded polystyrene).

The primary applications of CFC-11 in closed-cell foams were focused in the production of various PUR insulation products. Additionally, trace quantities of CFC-11 were used in phenolic insulation and polyolefin packaging foams. The introduction of phenolic foams for insulation applications was documented around 1981 (Wert et al., 1988). By 1993, phenolic foams constituted less than 5% of the global foam insulation market (FTCO, 1995). The global consumption of CFCs for phenolic foam production was estimated at 1.4 kt in 1986, rising to 2.7 kt in 1990, before declining to 0.6 kt in 1993 due to the phased-out of CFCs by non-article 5 (A5) parties (FTOC, 1995).

Polyolefin foams were versatile products made from polyethylene or polypropylene resins. They can be extruded into sheets, planks, or tubular forms, traditionally serving as protective packaging for furniture, flotation devices, and as cushioning for electronics or high-value goods (FTOC, 1991; 1995; 2002). In 2000, approximately 5.3 kt of blowing agents were deployed in the manufacture of extruded polyethylene foams, representing a mere 1.6% of the total volume of blowing agents used that year (FTOC, 2002). The emissions profile associated with CFCs from polyolefin foams was characterized by a prompt release pattern, with the majority of emissions occurring within two years post-production (FTOC, 1995; 2002). Given both the minor proportion of blowing agents used in polyolefin foams and their rapid emission characteristics, classifying CFC-11 usage within these applications as immediate emissive uses was relatively accurate and devoid of substantial error margins.

This study, considering the emission profiles of various foams and aiming for enhancing computational efficiency, categorized CFC-11 used in closed-cell foams into five distinct sub-sectors.

a) Appliance insulation. This sub-sector included insulation foams used in household refrigerators, freezers, and other appliances such as display cabinets, water heaters, portable coolers, commercial appliances, vending machines, etc (FTOC, 1991; 1995; 2002). In summary, this sub-sector included domestic refrigeration, commercial refrigeration and other appliances, and refrigerated containers, as detailed in Table S2.
b) Boardstock/laminate insulation. Constructed boardstock can be laminated with various facing materials, primarily used in building insulation, especially in commercial roof applications. Other uses included insulation for metal buildings, agricultural structures, cavity walls, and sheathing in residential construction. This sub-sector had historically been prevalent in non-Article 5 (non-A5) regions, particularly in North America, Europe, and Japan (FTOC, 1991; 1995; 2002). This sub-sector included PU boardstock as detailed in Table S2.
c) Continuous and discontinuous panel insulation. These panels, featuring foam cores between rigid facings, were designed to meet diverse needs of construction and industry such as cold storage facilities, retail stores, and factories (FTOC, 1991; 1995; 2002). This sub-sector included PU continuous and discontinuous panels as detailed in Table S2.
d) Spray foam insulation. Sprayed foams were commonly used for in situ rigid thermal insulation. Its primary uses were prevalent in roofing applications, particularly within the United States (U.S.). Worldwide, sprayed foams had been extensively used in residential and commercial buildings, industrial storage tanks, piping and ductwork systems, and refrigerated transport trailers and tanks (FTOC, 1991; 1995; 2002). This sub-sector included PU spray foam as in Table S2.
e) Other insulation, including continuous and discontinuous blocks. Historical market surveys suggested that CFC-11 in closed-cell foams was exclusively used for discontinuous blocks until the mid-1960s (McCulloch et al., 2001). This sub-sector also included pipe sections and

slabstock, which were manufactured into various shapes for insulation purposes such as storage tanks and boards (FTOC, 1991; 1995; 2002). This sub-sector included PU block and pipe, PU pipe in pipe, PU block foam slab, as detailed in Table S2.

S1.3 CFC-11 in North America closed-cell foams

Countries are categorized as non-A5 and article 5 (A5) parties under the Montreal Protocol. In this study, non-A5 parties include North America (comprising the United States (U.S.) and Canada), European nations designated as non-A5 (non-A5European parties), Japan and other non-A5 parties; whereas A5 parties consist of China and other countries recognized as A5 under the Montreal Protocol (other A5).

Our study quantitatively assessed regional CFC-11 consumption in various closed-cell foam subsectors, with a particular focus on its historical production of PUR foams and based on reasonable inferences. Previous studies have documented some historical estimates regarding PUR production and its applications (Bedoit, 1974; US.EPA, 1976; 1980). In the U.S., PUR foam production increased from negligible amounts in 1955 to approximately 5 kt by 1960. Since then, there had been a rapid growth in PUR foam production within the U.S. By 1975, the U.S. PUR foam production had further escalated to 174 kt (Hammitt et al., 1986). The Rand Corporation had provided historical estimates for various aspects of PUR foam production and CFC-11 consumption associated with these applications within the U.S. from 1978 to 1984 (Hammitt et al., 1986). In 1985, approximately 43 kt of CFC-11 were consumed in the production of 346 kt of PUR foam products in the U.S. (Wert et al., 1988). Missing values were estimated using linear extrapolation, and the annual production of PUR foam in the U.S. was depicted in Figure S2.

The introduction of phenolic foam into insulation applications in the U.S. occurred around 1981 (Wert et al., 1988). By 1985, the production of phenolic foam was approximately 10 kt, which involved the consumption of 1.4 kt of CFCs as blowing agents (Hammitt et al., 1986). PUR formulations typically contained 12–16% CFCs by weight (FTOC, 1995; 2002). In this study, with reference to the production of PUR foams across various regions and the consumption of CFC-11 in closed-cell foam recorded by AFEAS, it was assumed that an addition rate of CFC-11 at 16% in closed-cell foam persisted until around 1975. From 1980 onwards, the incorporation of CFC-11 into closed-cell foams in the U.S. had linear decreased to 13%. Due to a lack of specific data on PUR foam usage recorded in the U.S. prior to 1960, it was assumed that the consumption of CFC-11 in closed-cell foams mirrored a similar proportion as indicated by AFEAS records from that year.

As for subsectors, PUR foam was widely used as “other insulation” products until the mid-1960s (Hammitt et al., 1986; McCulloch et al., 2001). From that point onward, PUR foam emerged as construction and appliance insulation products. The extensive adoption of PUR foams in construction commenced earnestly following the 1973 oil crisis. By 1975, insulation applications had become predominant, comprised for 81.6% of the total usage, with construction (46%), refrigeration appliances (31.6%), and industrial insulation (4%) leading the way; non-insulation applications, such as furniture parts and packaging, accounted for the remaining 18.4% (Hammitt et al., 1986). The use of CFC-11 across different subsectors from 1976 to 1985 aligned with findings from previous studies (U.S.EPA, 1976; 1980; Wert et al., 1988). In 1985, 57% of PUR foams in the U.S. allocated to construction insulation, 25% to refrigeration appliance insulation, 8% to other insulation products, and the remaining 10% to non-thermal products (Wert et al., 1988). Starting in 1986, estimates regarding CFC consumption by each subsector were developed based on reports from the United Nations Environmental Programme (UNEP) Rigid and Flexible Foams Technical Options Committee (FTOC) series and adhered to the phase-out schedule for CFC use within the U.S. Missing data points were interpolated using linear method. Figure S3 illustrated the consumption of CFC-11 across each subsector of closed-cell foam within the U.S. Considering the relative contribution of U.S. gross domestic product (GDP) to the overall North American GDP, we employed a multiplier derived from this GDP proportion to estimate CFC-11 consumption across each subsector of closed-cell foam throughout North America.

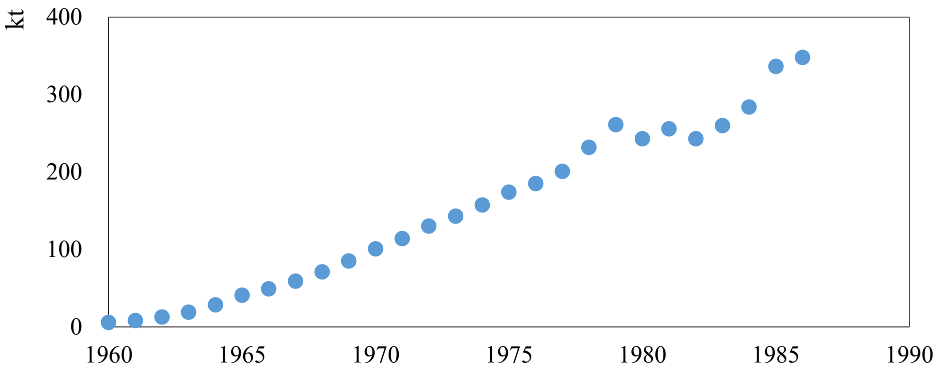

Figure S2 Annual production of polyurethane rigid foams in the United States

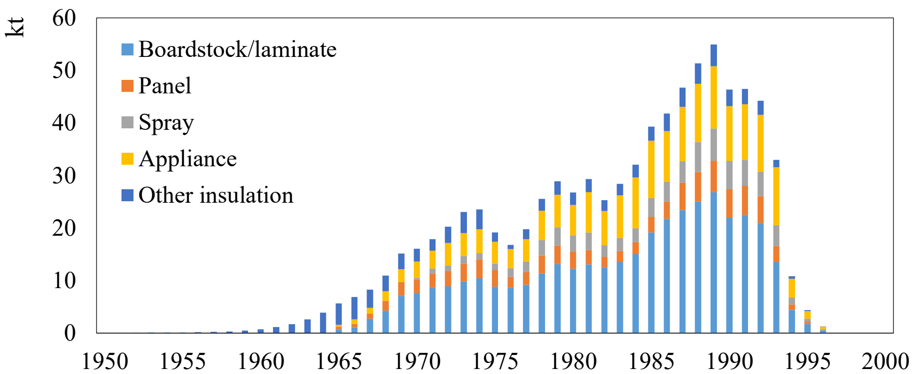

Figure S3 Annual CFC-11 consumption in each subsector of closed-cell foams in the United States

S1.4 CFC-11 in Japan closed-cell foams

In Japan, the production of PUR foams increased from approximately 1.3 kt in 1965 to 16 kt in 1970 (Japan METI, 2024). Subsequently, reports from the Japan Ministry of Economy, Trade and Industry (METI) have systematically provided estimates on the consumption of CFC-11 in closed-cell foams, detailing its allocation across various construction and appliance subsectors starting from 1971 onwards. For the period between 1965 and 1970, the consumption of CFC-11 within Japan's closed-cell foam industry was inferred based on PUR foam production volumes. In 1965, CFC-11 consumption across various closed-cell foam subsectors in Japan constituted a mere 1% of global CFC-11 sales for closed-cell foams, as recorded by AFEAS (2003). Prior to 1965, it was assumed that CFC-11 consumption in Japan's closed-cell foams accounted for a similar proportion relative to AFEAS (2003) records as observed in that year. Based on these assumptions, historical consumption patterns of CFC-11 across various subsectors of closed-cell foam in Japan was depicted in Figure S4.

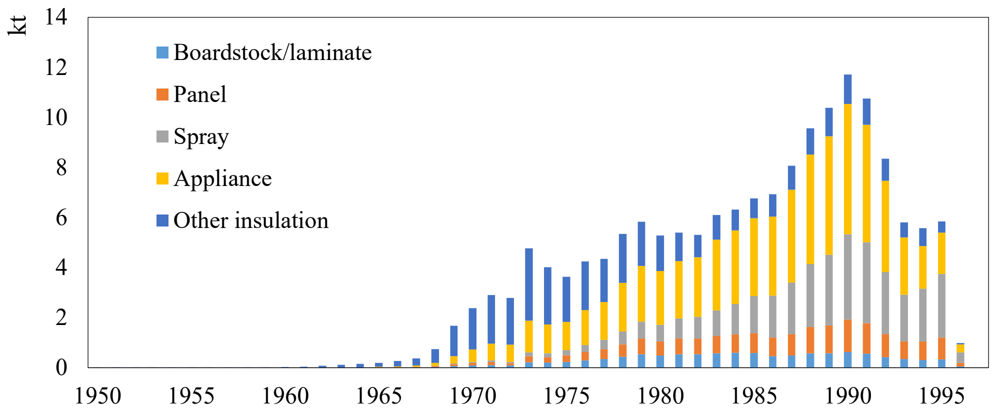

Figure S4 Annual CFC-11 consumption in each subsector of closed-cell foams in Japan

S1.5 CFC-11 in European non-Article 5 closed-cell foams

The consumption quantity of CFC-11 in closed-cell foam in Europe had historically mirrored those observed in the U.S. (Hammitt et al., 1986; Kendall et al., 1978). Considering the regional development of PUR foams, it was reasonable to assume that the sales data for CFC-11 in closed-cell foams recorded by AFEAS (2003) were distributed among the U.S., Japan, and European non-A5 parties from 1950 to 1965. This assumption was unlikely to introduce significant errors, particularly given that PUR foams did not achieve widespread use until the mid-1960s.

In 1970, production of PUR foam in the Western European was recorded at 75 kt (Kendall et al., 1978). From 1976 to 1981, historical use of CFC-11 in PUR foam production within the European Economic Community (EEC) was estimated to have increased from 20 to 35 kt (U.S.EPA, 1976). In terms of ozone depletion potential (ODP) perspective, CFC consumption in EEC countries accounted for approximately 64% of total CFC consumption in European non-A5 countries (UNEP, 2025). This proportion only slightly differed from the GDP ratio between EEC and European non-A5 countries, which stood at around 69% in 1986 (McCulloch et al., 1994). Factors reflecting this ratio were used to extrapolate PUR foam production volumes for European non-A5 countries until

1985. Starting from 1986 onwards, the consumption of CFC-11 across various types of closed-cell foams was meticulously documented in a series of FTOC reports (FTOC, 1991; 1995; 2002; 2006; 2010). In instances where data were incomplete, linear interpolation was employed to estimate missing values. The estimated CFC-11 consumption across different closed-cell foam subsectors in European non-A5 was illustrated in Figure S5.

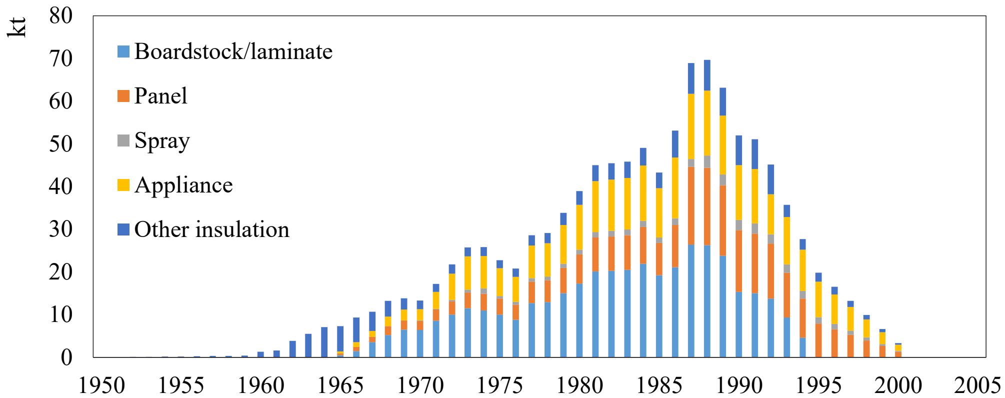

Figure S5 Annual CFC-11 consumption in each subsector of closed-cell foams in European non-A5 countries

S1.6 CFC-11 in China closed-cell foams

Research on PU foam in China commenced around 1958, with initial efforts focused on the production of PUF products. By the mid-1960s, China had developed the capability to produce PUR foams, which were primarily used in shipbuilding, cold storage, and insulation for petrochemical pipelines (Li et al., 1985). Despite this early adoption of technology, the growth of the industry remained slow and stagnant for approximately two decades.

In 1975, China's total production of PU foam, including both PUR and PUF foam, reached approximately 3.2 kt, with PUR foam accounting for 0.6 kt (Wang et al., 1999). By 1978, PU production had increased to 5 kt, with PUR foam contributing around 1 kt to this total. A significant surge in production occurred from around the year 1984 onwards when the overall PU output soared to an impressive 35 kt, while PUR foam alone reached a staggering volume of 15 kt. Notably, during this period, China’s combined production capacity for CFCs was merely approximately 7 kt, representing only 1% of the global output for these chemicals. By the year 2000, the production volumes of PUF and PUR foams in China had risen substantially to reach levels of 350 kt and 200 kt (Zhang et al., 2004), respectively. The consumption of CFC-11 in the production of PUR foams was reported at 13.6 kt in 1991 and escalated to 16.8 kt by 1997 (China MEE, 1993; 1999). Since 1999, CFC production within China had been strictly regulated under a quota licensing system that mandated manufacturers obtain a valid CFC production quota license. Unauthorized CFC manufacturing by any enterprises lacking this license was explicitly prohibited. Furthermore, the use of CFC-11 in PUR foams was completely phased out by January 1st, 2008 in China (China MEE, 2007; Hu et al., 2005).

Based on the production volumes of PUF and PUR foams in China, we have estimated the historical consumption of CFC-11 in closed-cell foam applications within the country. By 2000, closed-cell foams were primarily used for insulation purposes across various subsectors: appliances and transportation (42.5%), construction panels (18.5%), spray foams (19%), and other insulation applications (10%) such as chemical storage tanks and industrial equipment. The remaining 10% was attributed to a range of non-insulated applications (Wang et al., 2015). The estimated CFC-11 consumption across different closed-cell foam subsectors in China was presented in Figure S6.

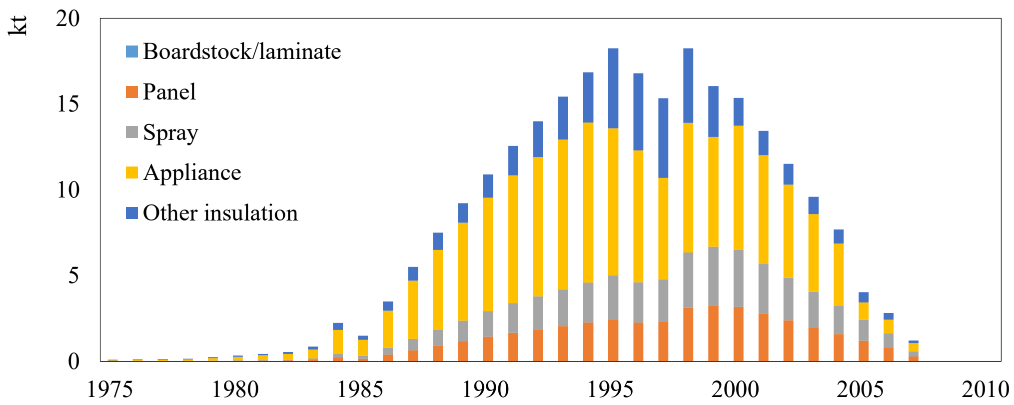

Figure S6 Annual CFC-11 consumption in each subsector of closed-cell foams in China

S1.7 CFC-11 in other non-A5 closed-cell foams

In 1970, Australia's production of PUR was recorded at 2.5 kt, accounting for approximately 1.3% of global PUR consumption and reflecting its share of the world GDP at that time (AFEAS, 2003; GDP, 2024). It was assumed that prior to 1985, GDP ratios from other non-A5 parties were used to scale down the sales of CFC-11 in closed-cell foams. From 1986 onwards, quantities for CFC-11 allocation derived from FTOC reports were used. It was further assumed that CFC-11 consumption across various subsectors of closed-cell foams before 1986 remained consistent with the levels documented in the FTOC report of that year. Linear interpolation methods were applied to address any missing data points. The estimated CFC-11 consumption in each foam subsector for other non-A5 parties was illustrated in Figure S7.

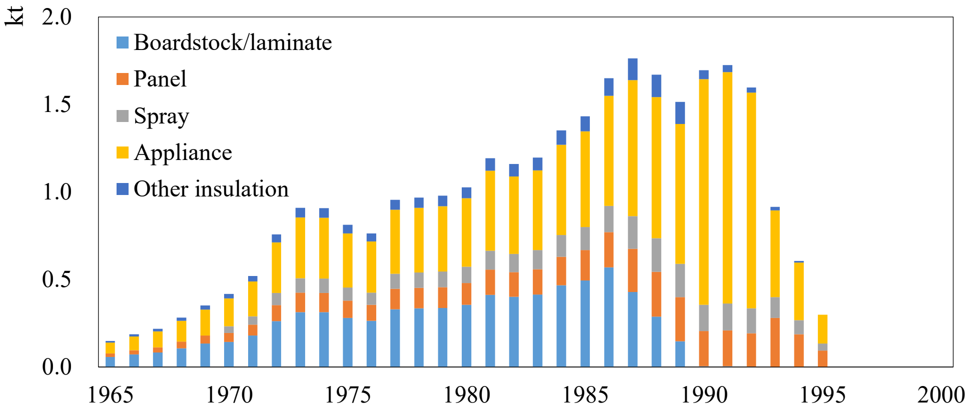

Figure S7 Annual CFC-11 consumption in each subsector of closed-cell foams in other non-A5 parties

S1.8 CFC-11 in other A5 closed cell foams

In 1970, the estimated production of PUR foams in other A5 countries was approximately 2.5 kt (Kendall et al., 1978). From 1986 onwards, the series of FTOC reports became the primary sources for tracking CFC-11 consumption in various closed-cell foam applications within other A5 countries (FTOC, 1991; 1995; 2002; 2006; 2010). In cases where was incomplete, linear extrapolation was employed to estimate the missing values. The phase-out of CFC use in A5 countries was successfully accomplished around 2008 (FTOC, 2010). Estimated CFC-11 consumption in each foam subsector in other A5 was illustrated in Figure S8.

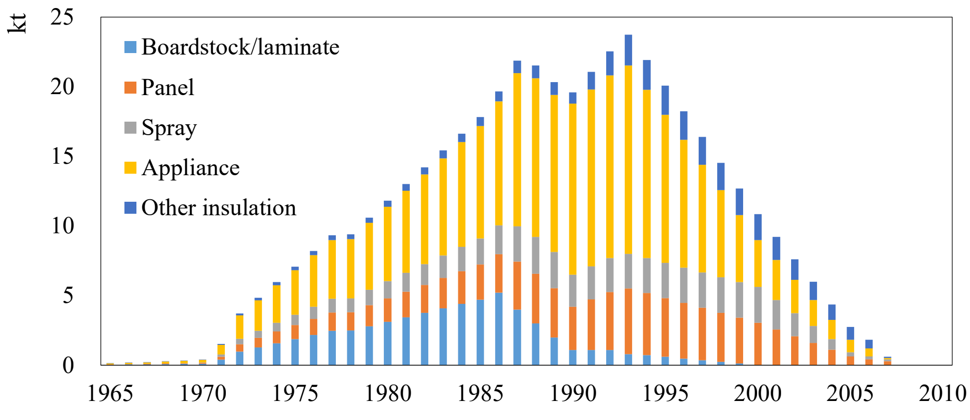

Figure S8 Annual CFC-11 consumption in each subsector of closed-cell foams in other A5 parties

S1.9 CFC-11 in global closed-cell foams

Prior to 1989, the coverage of AFEAS data on CFCs exceeded 80% when compared to UNEP data (AFEAS, 2003; McCulloch et al., 2001; UNEP, 2025). However, certain countries' production and sales were excluded from the AFEAS survey. As CFC production and use shifted from non-A5 parties to A5 parties, the coverage of UNEP data by AFEAS declined significantly to approximately

50% in 1994–1996 and further decreasing to only 12% in 2003 (McCulloch et al., 2001). In this study, after conducting a comprehensive analysis of CFC-11 use in closed-cell foams across different regions, we estimated global consumption patterns for CFC-11 within various subsectors of closed-cell foams from 1950 to 2010. The corresponding results were presented in Figure S9.

According to AFEAS (2003), data on CFC-11 usage in each closed-cell foam was counted together. McCulloch et al. (2001) estimated the worldwide use of CFC-11 in closed-cell foam between 1950 and 1999 using proportion derived from AFEAS data. Prior to 1993, our dataset fell somewhere between the records provided by AFEAS and those projected by McCulloch et al. (2001). The majority of closed-cell foams are predominantly employed in non-A5 regions such as North America, Europe, and Japan that time (TEAP, 2019). It was reasonable to assume that the proportion of CFC-11 used in closed-cell foam from unrecorded regions is relatively small. Subsequent to 1994, as non-A5 parties began reducing their reliance on CFCs, the sale values recorded by AFEAS for CFC-11 experienced a significant decline. However, during this timeframe, there may have been continued growth concerning the use of CFCs among A5 parties. Given these ongoing developments within A5 parties, it was justified that our estimates regarding post-1994 use levels for CFC-11 exceed those documented by AFEAS (2003) and McCulloch et al. (2001).

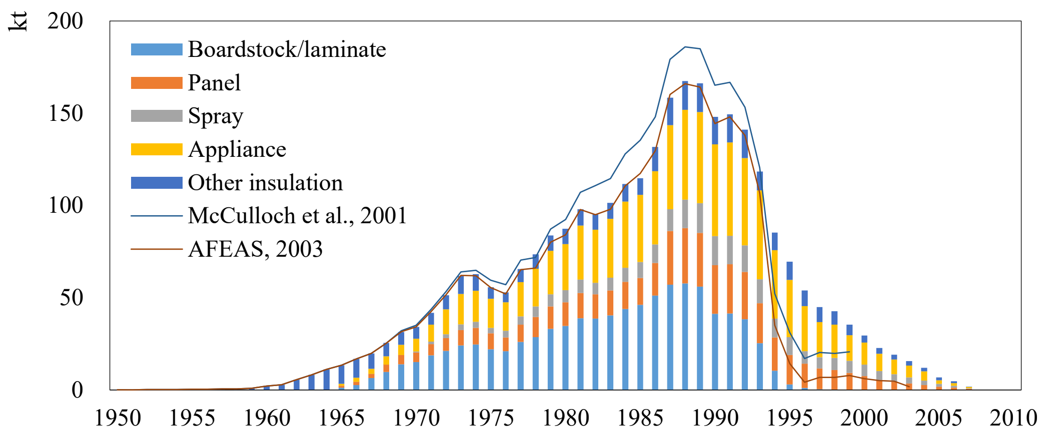

Figure S9 CFC-11 consumption in subsectors of global closed-cell foam in this study, compared with the findings from AFEAS (2003) and McCulloch et al. (2001).

S1.10 CFC-11 in non-hermetic refrigeration systems

In the context of refrigerants, CFC-11 usage has been classified under non-hermetic refrigeration systems. AFEAS documented annual sales data for this end-us application from 1931 to 2003. Clodic et al. (2010) and the UNEP Refrigeration, Air Conditioning, and Heat Pumps Technical Options Committee (RTOC) series of reports examined the demand for CFC refrigerants over several years. Notable differences were observed in the use of refrigerants within non-hermetic refrigeration systems, such as centrifugal chillers, among the U.S., Japan, and Europe. Specifically, CFC-12 was predominant used in Europe, while CFC-11 remained prevalent in the U.S. and Japan

(RTOC, 1994; 1998). Furthermore, it was noted that CFC-11 chillers were used less frequently in A5 parties compared to non-A5 parties. Prior to 2006, the majority of the centrifugal chiller market was concentrated within the U.S. (RTOC, 2006). Additionally, there existed a small proportion of CFC-11 employed in chillers designated for cleaning purposes (TEAP, 2019).

In this study, global data on CFC-11 used in non-hermetic refrigeration were aggregated based on regional consumption patterns within this end-use sector. In the U.S., the market for centrifugal chillers experienced significant growth from 1950 to 1964, but had fluctuated around 3,500 units per year since 1965 (U.S.EPA, 1976). During this period, approximately 80% of these units were charged with CFC-11. The annual domestic shipments of centrifugal chillers were documented between 1970 and 1984, showing an increase from 2,700 units to 3,400 units over that timeframe (U.S.EPA, 1980). It was assumed that each centrifugal chiller had an average charge of approximately 1.0 kt (Clodic et al., 2010). By analyzing domestic shipment data for chillers in the U.S. during the period from1970 to1984, it became possible to estimate CFC-11 consumption associated with new chillers during that timeframe. It was assumed that the rate of increase was similar to trends observed for CFC-11 consumption in non-hermetic refrigeration systems as recorded by AFEAS. Given that a significant portion of global CFC-11 consumption within non-hermetic refrigeration systems can be attributed to its use within the U.S., this assumption appeared reasonable. The phase-out of CFC-11 in new centrifugal chillers began in 1991, and was fully implemented by 1994 within the U.S (U.S.EPA, 2024). A linear reduction model for CFC-11 use was assumed between these years. Based on these data and assumptions, we initially estimated the quantity of CFC-11 used for filling new centrifugal chillers in the U.S.

In the mid-1970s, China's centrifugal refrigeration units underwent a comprehensive transition to indigenous design and manufacturing. However, due to their exclusive development for specific projects or specialized requirements, these system compressors were not developed into a product series (Liu et al., 2022). According to statistics from the China Refrigeration and Air Conditioning Industry Association, only 60 units were produced in 1990. In 1991, 0.15 kt CFC-11 was used for filling new chillers, and an additional 0.48 kt of CFC-11 was used for refilling existing chillers (China MEE, 1993). By 1997, a total of 0.7 kt of CFC-11 had been consumed by chillers, including both the filling for new equipment and the refilling of existed equipment (China MEE, 1999). The phase-out of CFC-11 used in filling new chillers in China was completed by the end of 2001 (Hu et al., 2005; Wan et al., 2009). Based on trend in total consumption of CFC-11 and employing linear interpolation to estimate missing values, this study estimated the quantities of CFC-11 used in non-hermetic refrigeration systems within China.

A positive correlation between CFC consumption and GDP was observed, as validated by the use of CFC-11 in refrigeration systems (RTOC, 1994; 2006). Around 2005, it was estimated that 13 kt and 1.3 kt of CFC-11 were stored in centrifugal chillers in the U. S. and Canada, respectively (RTOC, 2006). The ratio of CFC-11 banks in the U.S. and Canada corresponded to their GDP ratios at that time. It was assumed that around 24.2 kt of CFC-11 were stored in refrigeration systems worldwide circa 2005, with 31% allocated to the U.S. and 17% to other A5 countries. This distribution closely resembled the average GDP ratio between the U.S. and other A5 parties during this period. Therefore, it was justified to estimate CFC-11 consumption for filling new refrigeration systems based on the GDP proportions between the U.S. and other regions. Given the dominance of CFC-12 in Europe and CFC-11 in the U.S. for centrifugal chiller system (Clodic et al., 2010; RTOC, 1994), a scaling factor of 20% was applied prior to the phase-out of CFC in the U.S. From 1991 onwards, there has been a linear decline in CFC-11 usage within refrigeration systems across European non-A5 parties until it phased-out. Considering diverse consumption activities among different regions, a scaling factor of 90% was applied to adjust the GDP proportion between Japan and the U.S., with a similar factor being used for other non-A5 parties. For other A5 parties, considering the situation in China, a scaling factor of 50% was used to adjust estimates for CFC-11 consumption in refrigeration systems before its phase-down commenced in the U.S. Subsequently, GDP growth ratios were applied to estimate levels of CFC-11 consumption in other A5 parties until 2000. From 2001 onwards, there has been a linear decline in CFC-11 usage across other A5 parties until its complete phased-out. According to cumulative quantities reported by AFEAS, only 8% of the total sales of CFC-11 were allocated for non-hermetic refrigeration applications. This indicated that estimations regarding CFC-11 usage in refrigeration systems were unlikely to yield significant errors.

Figure S10 illustrated the distribution of CFC-11 in non-hermetic refrigeration systems across various regions. Approximately 25% of the CFC-11 recorded in AFEAS for non-hermetic applications was used in filling new refrigeration systems. Given that a significant portion of CFC-11 in these systems was used for servicing activities, such as refilling due to leaks, accidents, or maintenance, our estimation remained reasonable.

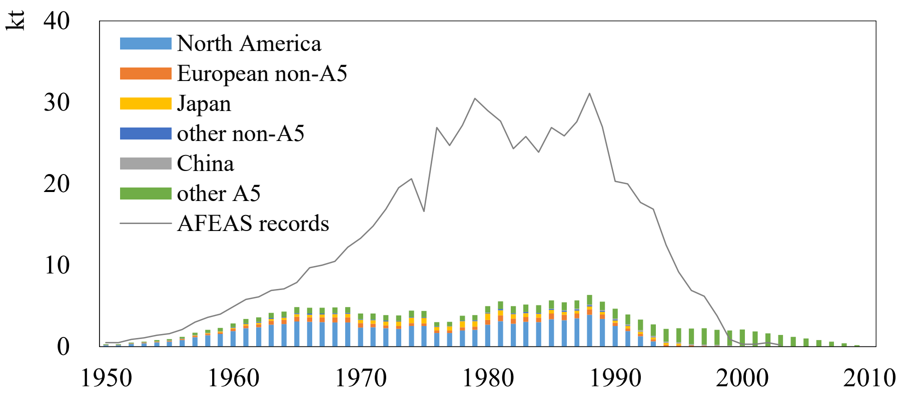

Figure S10 Estimation of CFC-11 consumption in new refrigeration systems across various regions, compared with CFC-11 sales data in non-hermetic refrigeration systems recorded by AFEAS (2003)

S1.11 Emissive uses

Within this sector, CFC-11 was used as aerosol propellants, solvents, blowing agents in open cell foams, and for other emissive applications. In this study, the consumption of CFC-11 for emissive uses was obtained by subtracting its use in closed cell foam and non-hermetic refrigeration systems (including refill quantities) from the total global consumption of CFC-11.

The U.S. International Trade Commission (ITC) had compiled production data on CFC-11 for specific years within the U.S. (Cook et al., 1996). During the early 1960s, more than 70% of the reported CFC-11 production submitted to AFEAS (2003) originated from the U.S. However, by 1984, this share had decreased to 34%. Figure S11 (a) presented historical records of CFC-11 production in the U.S.

McCulloch et al. (1998) provided data on the sales of CFC-11 within the European Union. By incorporating UNEP data regarding CFC consumption as ODP for European non-A5 parties and the European Union, we estimated the sales of CFC-11 within European non-A5 parties, as illustrated in Figure S11 (b).

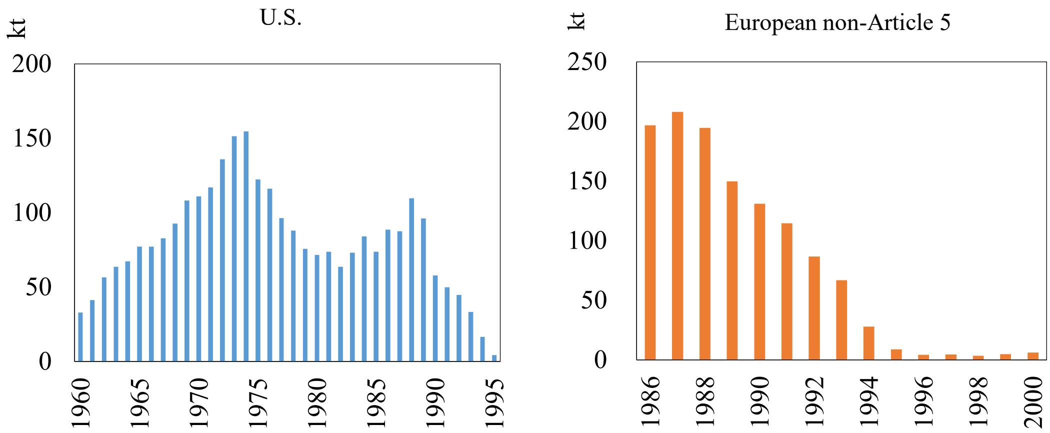

Figure S11 Historical production of CFC-11 in the U.S. and European non-Article 5 parties

In China, previous studies had estimated the consumption of CFC-11 and CFC-12 (Wang et al., 2010; Fang et al., 2018). We had referenced these specific consumption quantities in our analysis. Figure S12 presented a comparison between the consumption of CFCs and ODP based on data from UNEP (2025). The total consumption of CFC-11 and CFC-12 accounted for approximately 96% of the overall ODP attributed to various types of CFCs, including CFC-11, CFC-12, CFC-113, CFC-114, and CFC-115 in China.

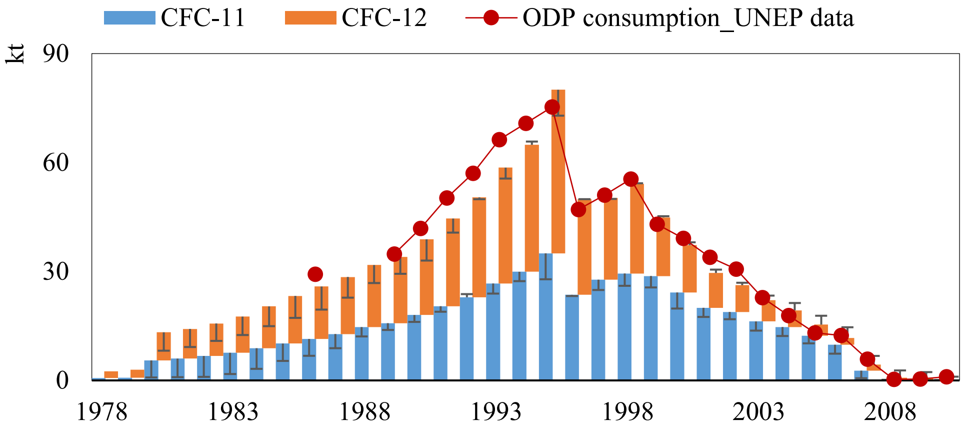

Figure S12 CFC-11 and CFC-12 consumption in China. Error bars represented the range of uncertainty associated with the results. Ozone depleting potential (ODP), United Nations Environment Programme (UNEP)

S2. Input parameters

S2.1 Parameters in non-hermetic refrigeration systems

In this study, ODP and 100-Year Global Warming Potential (GWP) values for CFC-11 were determined to be 1 and 4,750 (UNEP, 2024) respectively.

CFC-11, used as foam agents in closed-cell foams and as refrigerants in non-hermetic refrigeration systems, can accumulated within host products, resulting in delayed emissions. According to U.S. EPA reports, the emission factor (EF) during manufacturing (first-fill) was set at 0.5%, while the annual EF during the use stage was set at 20% for refrigeration systems. The EF associated with end-of-life (EoL) handling was stood at 20%, with the remainder being recovered properly. However, it was important to note that recovery and recycling of CFC-11 from obsolete non-hermetic refrigeration equipment proved uneconomical in the 1970s (U.S.EPA, 1976). In Japan METI reports, it was assumed that the EF of CFC-11 in non-hermetic refrigeration systems reached approximately 7% during the use stage, with an EoL EF estimated at approximately 43%. According to IPCC (1996), manufacturing EFs for factory built refrigeration systems were 2–3%, whereas those for systems erected and charged on-site were higher and at 4–5%. The average EF of CFC-11 in non-hermetic refrigeration equipment during its use stage was approximately 17%. By the early 1990s, some countries began implementing recovery and recycling practices aimed at reducing CFC emissions (IPCC, 1996). Given these variations in EFs across different lifecycle stages for CFC-11 in refrigeration systems, Table S7 presented the parameters used for calculating CFC-11 emissions from such systems within this study.

Reliable lifespan distribution data are essential for quantifying banks and flows. While TEAP (2019) relied on fixed mean lifespans for modeling CFC-11 emissions, TEAP (2021) subsequent adopted the Weibull distribution to better represent lifetime variability in the retirement patterns of refrigeration units and foam products. In this study, we similarly employ the Weibull distribution to characterize lifespan patterns for these categories. The Weibull parameters offer critical insights into the dynamic scrapping behavior of durable products. Specifically, the shape parameter defines the distribution skewness, indicating whether scrapping is more likely early (shape < 1), random (shape = 1), or delayed (shape > 1). The scale parameter, in turn, serves as an estimate of the average lifespan. Parameter estimates for foam products and refrigeration equipment were obtained from our surveys (Duan et al., 2018; Liu et al., 2024) and an extensive literature review (e.g., McCulloch et al., 2001; FTOC, 2002; IPCC, 2006; TEAP, 2021). Figure S13 illustrates the resulting remaining rate of refrigeration equipment over their lifespan, using the region-specific Weibull parameters listed in Table S7.

Table S7 Parameters for the emission profile of CFC-11 from non-hermetic refrigeration systems

Subsector	**Weibull distribution**		**Manufacturing**	**Use stage**	**EoL stage**
	Scale	Shape	**Emission factor (%)**	**Emission factor (% /year)**	**Recovery efficiency (%)**
	u	β	$Ef_{\mathrm{man}}(Y)$	$Ef_{\mathrm{use}}(Y)$	$\gamma_{EoL}(Y)$*
North America	25	3	2	10–20#	0–80
European non-A5	24	2.8	2	10	0–80
Japan	20	1.8	2	10	0–80
other non-A5	24	2.5	2	10	0–80
China	25	3.5	3	15	0–10
other A5	30	4	3	15	0–10

* Before 1990, the recovery efficiency was 0% across all regions, subsequently it increased linearly to 80%, 80%, 80%, 80%, 10% and 10% from 1995 onwards in various geographical regions.

Before 1980, the emission factor during the use stage was 20%, subsequently it decreased linearly to 10% starting from 1990 in the U.S.

It is assumed that the release of CFC-11 during the use stage can be refilled. Using this methodology, we estimated that approximately 190 kt of CFC-11 was used as the initial refrigerant charge in non-hermetic refrigeration systems, with an additional 600 kt applied as refill quantities during the usage stage for servicing and maintenance. These estimates align with previous records (AFEAS, 2003; Chine MEE, 1993).

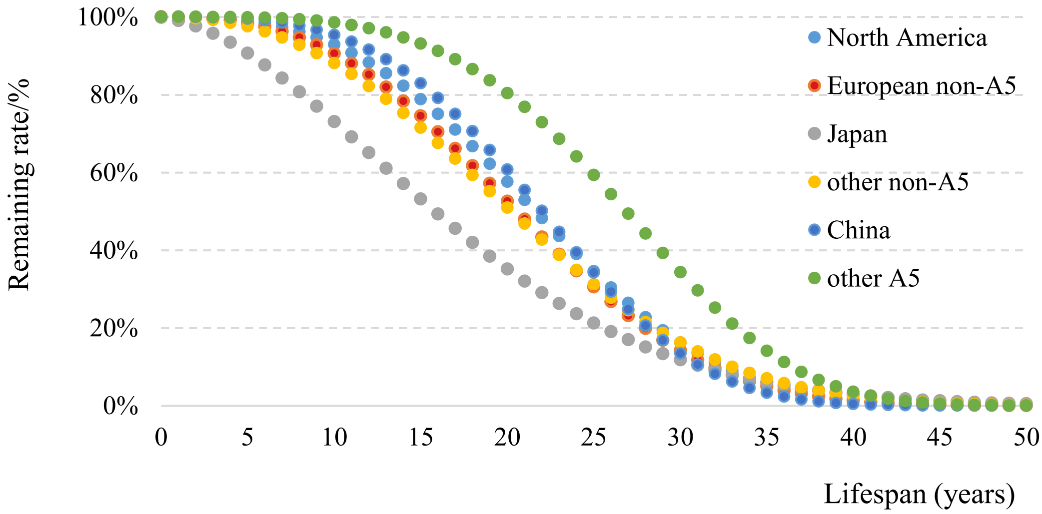

Figure S13 Curves depicting the correlation between remaining rate and lifespan of non-hermetic refrigeration equipment across different geographical region

S2.2 Parameters in closed-cell foams

McCarthy et al. (1977) used a simplified methodology to estimate CFC-11 emissions from closed-cell foams. They assumed an initial loss of 10% during the foam fabrication process, followed by a uniform annual loss rate of 4.5% over a period of two decades. This approach streamlined the estimation process and provided a more manageable framework for assessing the environmental impact of fluorocarbon emissions from PU foams over time. Gamlen et al. (1986) conducted an analysis to determine both the fastest and slowest likely release rates based on existing literature, concluding that the best estimate for release was perhaps the average of these two rates, which closely aligned with that derived from McCarthy et al. (1977) scenario. In 1997 and 1998, Caleb Management Services undertook a comprehensive global survey (McCulloch et al., 2001). This survey categorized CFC-11 emissions from closed-cell foams into various subsectors, such as PU continuous panels, PU discontinuous panels, PU appliances, PU laminates, PU sprays, and PU blown in situ, etc. Each subsector potentially exhibited its own distinct emission pattern. Subsequently, further studies (FTCO, 2002; IPCC, 2006; McCulloch et al., 2001) established release functions corresponding to various types of closed-cell foams.

The U.S. EPA, Japan MEIT, along with other previous studies (TEAP, 2019; 2021) used similar emission functions to calculate bottom-up emissions of CFC-11 from closed-cell foams. During the EoL stage, a portion of these obsolete foams had been disposed of in landfills. It was assumed that CFC-11, used as blowing agents in the foams entering landfills, continued to be released into the atmosphere. According to existing literature and our field survey (i.e., FTCO, 2002; IPCC, 2006; McCulloch et al., 2001; Duan et al., 2018; Liu et al., 2024), the parameters of estimating CFC-11 emissions from closed-cell foams were detailed in Tables S8-13.

Table S8 Mean parameter values for CFC-11 emission profile from closed-cell foams in North America (including the U.S. and Canada)

Subsector	Weibull distribution		Manufacturing	Use stage	EoL stage	Post-life stage
	Scale	Shape	Emission factor (%)	Emission factor (% /year)	Emission factor (%)	Emission factor (% /year)
	u	β	$Ef_{\mathrm{man}}(Y)$	$Ef_{\mathrm{use}}(Y)$	$Ef_{EoL}(Y)$	$Ef_{post}(Y)$
Appliances	16	2.5	5	0.5	35	1.5
Boardstock/ Laminate	50	6	6	1	45	1.5
Panel	50	6	8	0.5	45	1.5
Spray	50	6	20	1.5	100	1.5
Other insulation	15	2.6	35	1	50	1.5

Table S9 Mean parameter values for CFC-11 emission profile from closed-cell foams in European non-Article 5 (non-A5) and other non-A5 parties

Subsector	Weibull distribution		Manufacturing	Use stage	EoL stage	Post-life stage
	Scale	Shape	Emission factor (%)	Emission factor (% /year)	Emission factor (%)	Emission factor (% /year)
	u	β	$Ef_{\mathrm{man}}(Y)$	$Ef_{\mathrm{use}}(Y)$	$Ef_{EoL}(Y)$	$Ef_{post}(Y)$
Appliances	16.5	2.5	5	0.5	60	1.5
Boardstock/ Laminate	50	6	6	1	60	1.5
Panel	50	6	8	0.5	60	1.5
Spray	50	6	20	1.5	60	1.5
Other insulation	15	2.6	35	1	100	1.5

Table S10 Mean parameter values for CFC-11 emission profile from closed-cell foams in Japan

Subsector	Weibull distribution		Manufacturing	Use stage	EoL stage	Post-life stage
	Scale	Shape	Emission factor (%)	Emission factor (% /year)	Emission factor (%)	Emission factor (% /year)
	u	β	$Ef_{\text{man}}(Y)$	$Ef_{\text{use}}(Y)$	$Ef_{EoL}(Y)$	$Ef_{post}(Y)$
Appliances	11.8	2.8	5	0.5	100	1.5
Boardstock/ Laminate	25	6	6	1	32	1.5
Panel	48	6	8	0.5	10	1.5
Spray	48	6	20	1.5	10	1.5
Other insulation	15	2.6	35	1	100	1.5

Table S11 Mean parameter values for CFC-11 emission profile from closed-cell foams in China

Subsector	Weibull distribution		Manufacturing	Use stage	EoL stage	Post-life stage
	Scale	Shape	Emission factor (%)	Emission factor (% /year)	Emission factor (%)	Emission factor (% /year)
	u	β	$Ef_{\text{man}}(Y)$	$Ef_{\text{use}}(Y)$	$Ef_{EoL}(Y)$	$Ef_{post}(Y)$
Appliances	24	5	5	0.5	100	1.5
Boardstock/ Laminate	30	6	6	1	90	1.5
Panel	25	6	8	0.5	90	1.5
Spray	23	6	20	1.5	90	1.5
Other insulation	20	6	30	1	100	1.5

Table S12 Mean parameter values for CFC-11 emission profile from closed-cell foams in other Article 5 (A5) parties

Subsector	Weibull distribution		Manufacturing	Use stage	EoL stage	Post-life stage
	Scale	Shape	Emission factor (%)	Emission factor (% /year)	Emission factor (%)	Emission factor (% /year)
	u	β	$Ef_{\mathrm{man}}(Y)$	$Ef_{\mathrm{use}}(Y)$	$Ef_{EoL}(Y)$	$Ef_{post}(Y)$
Appliances	25	3.5	5	0.5	100	1.5
Boardstock/ Laminate	35	6	6	1	80	1.5
Panel	35	6	8	0.5	80	1.5
Spray	35	6	20	1.5	80	1.5
Other insulation	20	3.5	35	1	100	1.5

Table S13 Mean parameter values for the global CFC-11 emission profile from closed-cell foams

Subsector	Weibull distribution		Manufacturing	Use stage	EoL stage	Post-life stage
	Scale	Shape	Emission factor (%)	Emission factor (% /year)	Emission factor (%)	Emission factor (% /year)
	u	β	$Ef_{\mathrm{man}}(Y)$	$Ef_{\mathrm{use}}(Y)$	$Ef_{EoL}(Y)$	$Ef_{post}(Y)$
Appliances	20	3	5	0.5	60	1.5
Boardstock/ Laminate	50	6	6	1	50	1.5
Panel	50	6	8	0.5	50	1.5
Spray	50	6	20	1.5	90	1.5
Other insulation	15	2.6	35	1	70	1.5
non-hermetic	25	3.0	2	15	20	0

S2.3 Probability distribution for parameters

The parameters pertaining the lifetimes and EFs of closed-cell foam products containing CFC-11 demonstrated significant variability across diverse literature sources (Tables S2–3). This variability was further exacerbated by diverse range of foam products, such as boardstock, panel, and spray, each characterized by its own unique set of modelling parameters. Consequently, this complexity posed substantial challenges in verifying bottom-up emission estimates.

Prior research conducted by TEAP (2019; 2021) had extensively examined the emission uncertainties associated with CFC-11 production, its end-use breakdowns, and EFs. However, conventional methodologies tended to employ typical values to account for parameter variability, inadequately captured the dynamic nature of these factors. For instance, PUR boardstock and panel foams, which had been widely used as building insulation materials, were typically assigned lifespan estimates of 25, 50, or 75 years, and the estimated lifespan of appliance foam was typically around 15 years (Tables S2−3). To delve deeper into the uncertainties stemming from the interaction between foam product lifespans and EFs associated with lifecycle stages, we conducted a comprehensive analysis by synthesizing available data. We posited that Weibull scale and shape parameters, along with EFs related to manufacturing and use stages, were variables following distributions. Mean values of parameters relevant to CFC-11 emission profiles for global and regional closed-cell foams outlined in Tables 8−13. For instance, this study established the average lifespans for global boardstock, panel, and spray foams at 50 years. In contrast, the lifespans for appliances and other forms were determined to be 20 years and 15 years, respectively. These lifespans were then modeled as normal distributions centered on their corresponding mean values, with standard deviation set at 25% of the mean lifespans. To ensure that all values remained non-negative, a non-standard normal distribution approach was employed. This was illustrated in Figure S14, which depicted the distribution patterns of Weibull scale and shape parameters, along with EFs during manufacturing and usage stages in Table S13. The 99% confidence intervals for the scale, shape, Ef_{man}, and Ef_{use} parameters are as follows: 18.1–82.7 years, 2.2–9.8, 2.2%–9.9%, and 0.4–1.6%, respectively. By considering the distribution of parameters associated with the lifecycle of CFC-11-containing products, this study covered a broader spectrum of possible values, thereby providing a more accurate representation of CFC-11 flows, banks and emissions.

Globally, closed-cell foam products containing CFC-11 were used in a variety of insulation applications. For instance, PUR boardstock was extensively employed for commercial roof insulation as well as the walls of metal and agricultural buildings. PUR panels found applications in industrial settings such as cold storage facilities, retail stores, and factories. The typical assumption about the lifespan of buildings and their insulation foam products was approximately 50 years. However, actual lifetimes could vary significantly across different spatial and temporal contexts (Tables S2−3). Given this variability among insulation foam products used in buildings, our assumption regarding the lifespans of those containing CFC-11 remained reasonable.

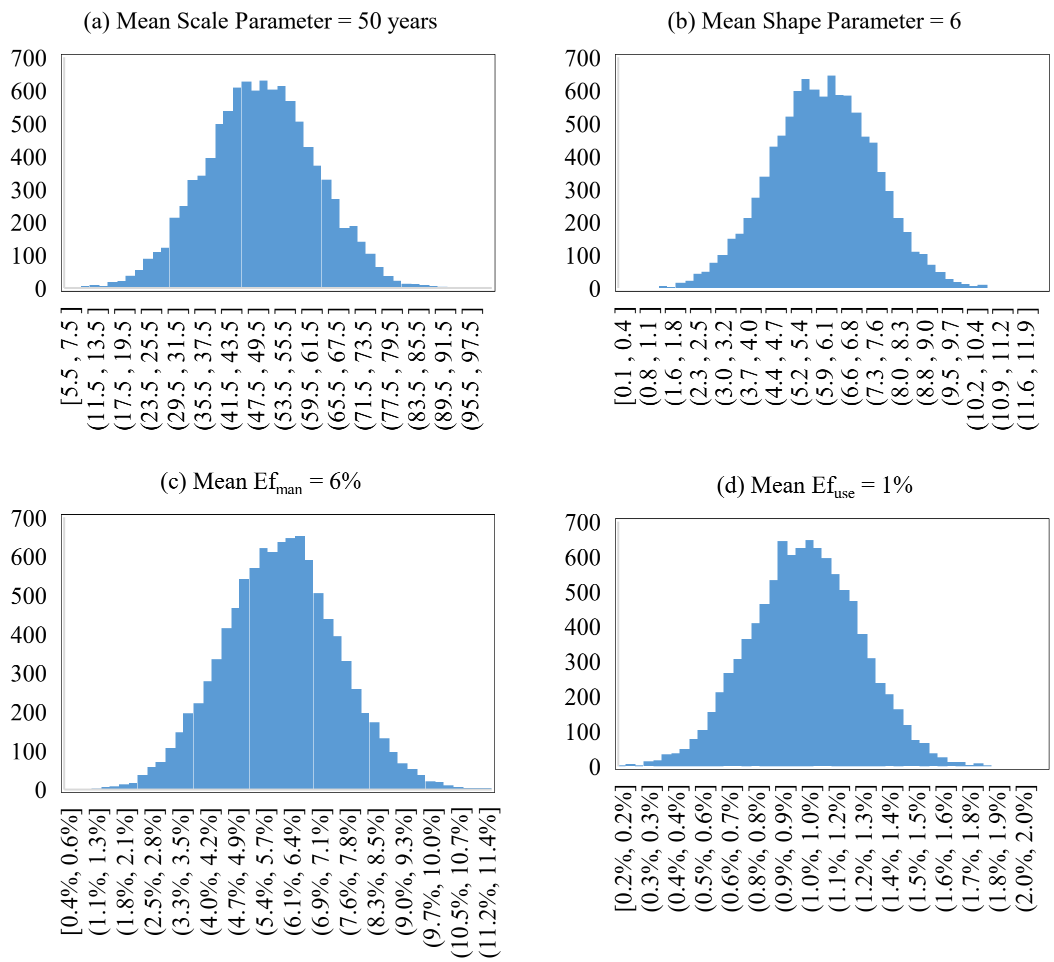

Figure S14 Distribution of key parameters in this study: Weibull scale (a) and shape parameters (b), along with emission factors during the manufacturing (c) and use stage (d) for polyurethane rigid boardstock/laminate foam products. $N=10^4$

Table S14 Parameter values for the global material flow of CFC-11 from closed-cell foams in the main text Fig.1c

Subsector	Weibull distribution		Manufacturing	Use stage	EoL stage	Post-life stage
	Scale	Shape	Emission factor (%)	Emission factor (% /year)	Emission factor (%)	Emission factor (% /year)
	u	β	$Ef_{\mathrm{man}}(Y)$	$Ef_{\mathrm{use}}(Y)$	$Ef_{EoL}(Y)$	$Ef_{post}(Y)$
Appliances	25	3.8	5	0.5	100	1.5
Boardstock/ Laminate	38	8	6	1	100	1.5
Panel	38	6	8	0.5	100	1.5
Spray	50	6	20	1.5	100	1.5
Other insulation	15	3.0	35	1	100	1.5

S3. Other results

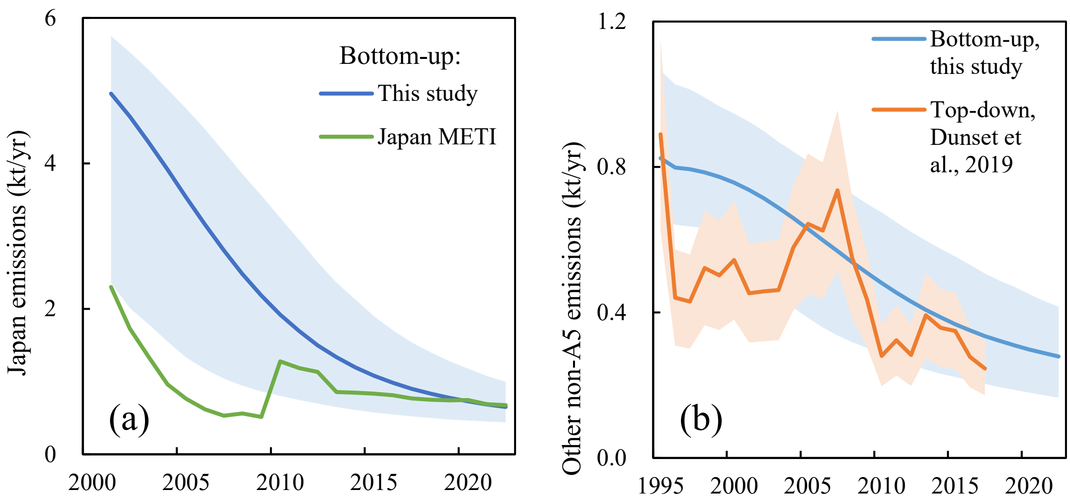

Figure S15 Comparison of CFC-11 emissions in Japan (a) and other non-A5 parties (b)

Japan METI revised its emission calculation methodology over time. Prior to 2010, CFC-11 emissions from closed-cell foam in the construction industry were calculated by applying a 3.3% annual release factor to the bank of CFC-11 in installed foams, which was adjusted yearly by subtracting a 3.3% loss. Beginning in 2010, the calculation base shifted to the cumulative initial charge, resulting in a marked increase in reported emissions. Starting in 2013, METI adopted the 2006 IPCC Guidelines, which use product-specific emission factors, leading to smoother and more consistent emission trajectories after 2013.

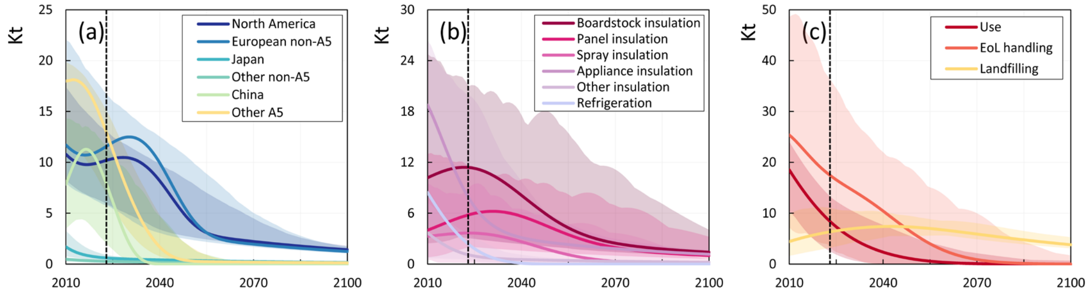

Figure S16 Banked CFC-11 emissions categorized by region (a), sector (b), and life stage (c)

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