Efficient Appliances for People & the Planet

Global Refrigerant Impact from 6 Appliances in 22 Countries

17 MAY 2022

Executive Summary

This report estimates the impacts of refrigerants found in six commonly used appliances in 22 key countries around the world. The six appliances predominantly feature heat pumps that transfer heat between a conditioned space and the ambient air. Within the heat pump, a refrigerant expands from a liquid to a gaseous state, absorbing heat from one of the spaces. The heat pump then moves the gas to the second space and condenses it back into a liquid, which causes the refrigerant to reject the stored heat into the second space. The refrigerant then returns to the start of the loop and repeats the process.

The refrigerants used in the six appliances are often potent greenhouse gases (GHGs) with global warming potential (GWP) thousands of times higher than CO_2, so even a few kilograms of leakage can result in emissions that surpass those from power generation. This report describes the process of collecting refrigerant data and estimating the leakage and the resultant GWP. The refrigerant data and the subsequent outputs will be integrated into CLASP's Mepsy Appliance & Equipment Climate Impact Calculator, with the hopes of informing countries of the impacts refrigerants have on global emissions and influencing policy decisions that would abate them.

Our modeling shows that in the key countries, emissions from refrigerants over 100 years and 20 years are 852 Mt CO_2e and 1825 Mt CO_2e, respectively. For comparison, these emissions are 13 to 29% of the CO_2 emitted while powering seven of the most common appliances in the 22 countries.[1] The significant portion that refrigerants contribute to global emissions highlights the need for more stringent policy action that mitigates high-GWP refrigerant usage and improve the recovery of refrigerants at the end of appliance life.

Introduction

[1] Total country emissions were calculated using Mepsy.

The equations used in CLASP's refrigerant impact model were derived from the 2021 California Public Utilities Commission's Refrigerant Avoided Cost Calculator. ATMOsphere (previously called Shecco) gathered data for 22 countries from public sources and manufacturer and proprietary market data when possible. These were supplemented by CLASP data in countries where CLASP conducts research and information on refrigerant GWPs sourced from the IPCC's 2014 Fifth Assessment Report (AR5), the World Meteorological Organization's 2018 Scientific Assessment of Ozone Depletion (SAP), and RTOC's 2018 Assessment Report.

CLASP and ATMOsphere researched and modeled the following appliances:

- **Residential Scale Air Conditioner:** Typically a split system, which contains an outdoor compressor and heat exchanger connected to one or multiple indoor air handlers.
- **Residential Scale Heat Pumps:** Like residential scale AC, but also includes a reversing valve, which allows for heating as well as cooling.
- **Residential Heat Pump Water Heaters:** Pulls heat from the surrounding air and transfers it (at a higher temperature) to heat water in a storage tank.
- **Commercial Refrigerated Display Cases (Plug-ins, Condensing Units, and Centralized):**
    - **Plug-ins:** Work like a household refrigerator and have the compressor, condenser and controller unit built into the cabinet itself. They only need a power supply.
    - **Condensing Units:** Typically used for smaller commercial spaces. A remote refrigeration system consists of an insulated cabinet for cold food storage that has the evaporator and ductwork built in. The condenser and compressor, meanwhile, are located in a separate unit connected to the cabinet by a pair of lines that transport coolant between the two.
    - **Centralized:** Have a common central condensing system which supplies several units with the refrigerant. The cabinets have a fixed location and are connected with pipes and wires to the central compressor rack and controller unit.

This list includes nearly all appliances that have heat pumps in them. Domestic refrigerators were omitted from this research due to their smaller refrigerant charge size, self-contained nature (less leakage than field-installed products) and earlier shift to using lower-GWP refrigerants. These three factors make their direct GHG emissions much smaller compared to the other appliances. GIZ estimates that global direct emissions from domestic refrigerators was only 14.4 Mt CO_2e in 2020, compared to 331 Mt CO_2e from residential air conditioners, despite there being twice as many domestic refrigerators as residential ACs.[2]

This model will be integrated into Mepsy, which already models the indirect GHG impact from many of these appliances. Commercial scale ACs are not currently available in Mepsy and so were excluded from this analysis.

Data

The following are the key countries researched by ATMOsphere: Japan, Thailand, Italy, U.S., U.K., Germany, Pakistan, South Africa, China, Brazil, India, France, Mexico, Turkey, Kenya, Australia, Egypt, Ghana, Lebanon, Grenada, Moldova and Poland. A "Generic Article 5" country profile was also developed to represent other countries that lack strong energy efficiency policies and fall under Article 5 of the Montreal Protocol on Substances that Deplete the Ozone Layer and its Kigali Amendment on phasing down hydrofluorocarbons (HFCs).

CLASP will use data sourced from these countries to generalize results globally. The countries selected for data collection and the associated countries categorized under each grouping are based on UNEP's 2010 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee. The following table displays the country groupings used.

COUNTRY GROUPINGS

REGION	COUNTRIES	ARTICLE 5/ NON-ARTICLE 5	REPRESENTATIVE COUNTRY
South America	Argentina, Bolivia, Brazil, Chile, Colombia, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela	A5	Brazil
Central America	Belize, Costa Rica, El Salvador, Honduras, Guatemala, Mexico, Nicaragua, Panama,	A5	Mexico
North America	Canada, United States	Non-A5	USA
Caribbean	Antigua, Bahamas, Barbados, Cuba, Dominica, Dominican Republic, Grenada, Haiti, Jamaica, Saint Lucia, St Kitts and Nevis, St Vincent, Trinidad and Tobago	A5	Grenada
Egypt	Egypt	A5	Egypt

REGION	COUNTRIES	ARTICLE 5/ NON-ARTICLE 5	REPRESENTATIVE COUNTRY
Southern Africa	Botswana, Lesotho, Namibia, South Africa, Swaziland	A5	South Africa
Western Africa	Benin, Burkina Faso, Cape Verde, Côte d'Ivoire, Equatorial Guinea, Gambia, Ghana, Guinea, Mali, Guinea-Bissau, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo	A5	Ghana
Other African Countries	Algeria, Angola, Cameroon, Central African Republic, Chad, Congo, Congo, Dem. Rep. of the, Gabon, Liberia, Libyan Arab, Jamahiriya, Morocco, Sao Tome, Seychelles, Somalia, Sudan, Tunisia, Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, (U. Rep. of) Tanzania, Uganda, Zambia, Zimbabwe	A5	Kenya
Turkey	Turkey	A5	Turkey
Lebanon	Lebanon	A5	Lebanon
Israel	Israel	Non-A5	40% Lebanon 60% Turkey
Western Asia	Bahrain, Qatar, Saudi Arabia, Oman, Kuwait, United Arab Emirates	A5	40% Lebanon 60% Turkey
Central Asia	Tajikistan, Uzbekistan, Kazakhstan, Afghanistan, Armenia, Georgia, Iraq, Jordan, Kyrgyzstan, Syrian Arab Republic, Turkmenistan, Yemen, Azerbaijan,	A5	Generic A5

REGION	COUNTRIES	ARTICLE 5/ NON-ARTICLE 5	REPRESENTATIVE COUNTRY
Southern Asia	Bangladesh, Bhutan, Maldives, Sri Lanka, Nepal, Myanmar, India, Iran, Islamic Rep. of, Pakistan	A5	India
Eastern Asia	Hong Kong, China (SAR)	Non-A5	40% China 60% Japan
Eastern Asia	China, Korea, Rep. of, Macau, Mongolia, North Korea	A5	China
Eastern Asia	Japan	Non-A5	Japan
Southeastern Asia	Brunei Darussalam, Cambodia, Indonesia, Lao People's Dem. Rep., Malaysia, Thailand, Philippines, Singapore, Viet Nam	A5	Thailand
Oceania	Australia, New Zealand	Non-A5	Australia
Oceania	French Polynesia	Non-A5	50% France 50% Australia
Oceania	Cook Islands, Fiji, Kiribati, Marshall Islands, Micronesia, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu	A5	Generic A5
EU 27	Finland, Greece, Monaco,	Non-A5	France
	France	Non-A5	France
	Austria, Luxembourg, Netherlands, Sweden, Switzerland, Belgium, Germany, Denmark	Non-A5	Germany
	Italy, Portugal, Spain, Greece	Non-A5	Italy
	Other EU: Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania,	Non-A5	Poland

REGION	COUNTRIES	ARTICLE 5/ NON-ARTICLE 5	REPRESENTATIVE COUNTRY
	Malta, Poland, Romania, Slovakia, Slovenia		
UK & Ireland	United Kingdom, Ireland	Non-A5	UK
Other Europe	Andorra, Iceland, Liechtenstein, Ukraine, Belarus, Russian Federation	Non-A5	Moldova
Other Europe	Albania, Bosnia and Herzegovina, Croatia, Moldova, Rep. of, Montenegro, Serbia, (TFYR) of Macedonia	A5	Moldova

The following tables show the key information used to model the total annual emissions from refrigerants over an appliance's lifetime. (Refer to 'Model Inputs' list to identify column headings; blank rows indicate that the product is not typically used in the country and region.) It is also important to note that only the highest volume refrigerant was listed in this input table for the sake of saving space; however, our model utilizes the main four refrigerants for each country and product.

RESIDENTIAL SCALE AC DATA

COUNTRY	APPLIANCE SIZE (KW)	N (YEARS)	M (KG)	L_{ANNUAL}	t_EOL	α_{EOL}	MAIN REFRIGERANT
Japan	3.9	9	0.9	2%	1	67%	R32, 80%
Thailand	4.9	9	0.9	6%	3	100%	R410A, 62%
Italy	5.0	9	2.3	3%	1	50%	R410A, 72%
U.S.	5.0	13	1.75	6%	1	80%	R410A, 96%
U.K.	5.0	9	1.5	3%	1	30%	R410A, 90%
Germany	5.0	9	1.1	3%	1	36%	R410A, 85%
Pakistan	5.0	9	1.5	10%	3	100%	R22, 90%
South Africa*	5.0	9	0.73	5%	3	97%	R410A, 55%

COUNTRY	APPLIANCE SIZE (KW)	N (YEARS)	M (KG)	L_{ANNUAL}	t_EOL	α_{EOL}	MAIN REFRIGERANT
China*	3.9	9	0.96	10%	3	100%	R410A, 60%
Brazil	5.2	9	0.6	31%	3	99%	R22, 80%
India*	5.0	9	0.21	10%	3	100%	R22, 77%
France	5.0	9	2.75	4%	1	35%	R410A, 99%
Mexico	4.6	9	3	10%	3	95%	R22, 98%
Turkey	6.4	9	2.75	10%	3	90%	R410A, 95%
Kenya	5.0	9	2.6	13%	3	100%	R410A, 69%
Australia	5.0	9	1.15	4%	1	10%	R410A, 50%
Egypt	5.0	10	1.25	10%	3	100%	R410A, 65%
Ghana	5.0	9	1.68	23%	3	95%	R22, 79%
Lebanon	5.0	9	0.9	10%	3	95%	R410A, 58%
Grenada	5.0	9	1.25	10%	3	95%	R410A, 100%
Moldova	5.0	9	0.9	10%	3	60%	R410A, 45%
Poland	5.0	9	0.9	4%	1	40%	R410A, 99%
Generic A5	5.0	20	1.5	10%	3	65%	R22, 90%

RESIDENTIAL SCALE HEAT PUMPS DATA

COUNTRY	APPLIANCE SIZE (KW)	N (YEARS)	M (KG)	L_{ANNUAL}	t_EOL	α_{EOL}	MAIN REFRIGERANT
Japan	5.37	25	0.9	2%	1	67%	R32, 80%
Thailand	/	/	/	/	/	/	/
Italy	5.37	25	2.25	3%	1	50%	R410A, 72%
U.S.	10	25	1.75	6%	1	80%	R410A, 96%
U.K.	5.37	25	3	6%	1	35%	R410A, 80%
Germany	5.37	25	1.125	3%	1	36%	R410A, 85%
Pakistan	5.37	25	2.6	10%	3		R410A, 57%
South Africa**	5.37	25	0.73	5%	3	97%	R410A, 55%
China	5.37	25	2.6	10%	3	100%	R410A, 60%
Brazil	/	/	/	/	/	/	/
India	/	/	/	/	/	/	/
France	5.37	25	3.2	4%	1	35%	R410A, 90%
Mexico	/	/	/	/	/	/	/
Turkey	5.37	25	2.75	6%	3	90%	R410A, 95%
Kenya	/	/	/	/	/	/	/
Australia	/	/	/	/	/	/	/
Egypt	/	/	/	/	/	/	/
Ghana	/	/	/	/	/	/	/
Lebanon	/	/	/	/	/	/	/
Grenada	/	/	/	/	/	/	/
Moldova	5.0	9	0.9	10%	3	60%	R410A, 45%
Poland	/	/	/	/	/	/	/
Generic A5	5.37	25	2.6	10%	3	65%	R410A, 50%

RESIDENTIAL SCALE HEAT PUMP WATER HEATER DATA

COUNTRY	N (YEARS)	M (KG) 1	L_{ANNUAL}	t_EOL	α_{EOL}	MAIN REFRIGERANT
Japan	15	1.5	1%	1	55%	R744, 99%
Thailand	15	1.5	2%	3	100%	R410A, N/A
Italy	15	2.35	4%	1	99%	R410A, 95%
U.S.	15			1	100%	R134A, 88%
U.K.	15	0.3	4%	1	35%	R410A, 38%
Germany	15	0.8	2%	1	35%	R134A, 95%
Pakistan	/	/	/	/	/	/
South Africa	15	1.25	2%	3		R410A, 85%
China	15	3.15		3	100%	R22, 87%
Brazil	/	/	/	/	/	/
India	/	/	/	/	/	/
France	15	3.2	4%	1	35%	R410A, 90%
Mexico	/	/	/	/	/	/
Turkey	/	/	/	/	/	/
Kenya	/	/	/	/	/	/
Australia	15	0.9	3%	1	10%	R134A, 75%
Egypt	/	/	/	/	/	/
Ghana	/	/	/	/	/	/
Lebanon	/	/	/	/	/	/
Grenada	/	/	/	/	/	/
Moldova	/	/	/	/	/	/
Poland	/	/	/	/	/	/
Generic A5	15	2.2	6%	3	65%	R22, 43%

PLUG-INS

COUNTRY	N (YEARS)	M (KG) 1	L_{ANNUAL}	t_EOL	α_{EOL}	MAIN REFRIGERANT
Japan	12	2.2	3%	1	55%	R404a, 80%
Thailand	12	2.2	3%	3	100%	R404a, 70%
Italy	15	0.5	10%	1	12.5%	R744, 80%
U.S.	12	0.3	1%	1	58%	R404a, 43%
U.K.	18	0.5	2%	1	40%	R134a, 65%
Germany	12	0.6	1%	1	46%	R134a, 70%
Pakistan	12	0.6	2%	3	100%	R404a, 49%
South Africa	12	0.6	2%	3	80%	R134a, 41%
China	12	0.6	2%	3	100%	R404a, 49%
Brazil	12	0.6	2%	3	98%	R404a, 49%
India	12	0.3	2%	3	100%	R134a, 70%
France	7	0.3	1%	1	90%	R134a, 80%
Mexico	10	0.7	2%	3	90%	R134a, 100%
Turkey	12	0.6	2%	3	90%	R410A, 70%
Kenya	12	0.6	2%	3	100%	R404a, 49%
Australia	12	0.5	7%	1	90%	R134a, 75%
Egypt	12	0.6	2%	3	80%	R134a, 41%
Ghana	12	0.28	3%	3	80%	R134a, 82%
Lebanon	12	0.4	3%	3	80%	R134a, 69%
Grenada	12	0.4	3%	3	80%	R404a, 50%
Moldova	12	0.4	3%	3	70%	R600A, 45%
Poland	12	0.24	0.5%	1	90%	R410A, 70%
Generic A5	12	0.4	2%	3	78.5%	R404a, 49%

CONDENSING UNITS

COUNTRY	N (YEARS)	M (KG) 1	L_{ANNUAL}	t_EOL	α_{EOL}	MAIN REFRIGERANT
Japan	14	6.0	13%	1	55%	R404a, 80%
Thailand	14	6.0	28%	3	100%	R404a, 70%
Italy	15	6.0	10%	1	12.5%	R744, 80%
U.S.	14	5.5	13%	1	58%	R404a, 43%
U.K.	18	5.0	11%	1	40%	R404a, 80%
Germany	14	5.0	10%	1	46%	R404a, 53%
Pakistan	14	3.0	10%	3	100%	R22, 90%
South Africa	10	3.0	10%	3	85%	R507, 67%
China	14	3.0	10%	3	100%	R22, 90%
Brazil	14	3.0	10%	3	98%	R22, 90%
India	14	3.0	10%	3	100%	R134a, 70%
France	12	3.6	12%	1	74.5%	R507a, 41%
Mexico	20	13.0	5%	3	90%	R22, 60%
Turkey	14	13.3	17%	3	90%	R410A, 70%
Kenya	14	9.7	15%	3	100%	R22, 90%
Australia	14	6.0	12%	1	95%	R404A, 80%
Egypt	10	3.0	10%	3	85%	R507, 67%
Ghana	14	20.9	30%	3	85%	R404a, 84%
Lebanon	14	5.0	20%	3	100%	R134a, 69%
Grenada	10	4.0	10%	3	80%	R404a, 100%
Moldova	10	6.0	3%	3	70%	R600A, 45%
Poland	14	3.2	12%	1	74.5%	R410A, 70%
Generic A5	14	4.0	10%	3	62.5%	R22, 90%

CENTRALIZED

COUNTRY	N (YEARS)	M (KG) 1	L_{ANNUAL}	t_EOL	α_{EOL}	MAIN REFRIGERANT
Japan	/	/	/	/	/	/
Thailand	/	/	/	/	/	/
Italy	15	500.3	10%	1	12.5%	R744, 80%
U.S.	16	101.0	20%	1	90%	R404a, 43%
U.K.	18	1550.0	9%	1	8%	R404a, 80%
Germany	16	1550.0	19%	1	22.4%	R134a, 70%
Pakistan	16	1520.0	13%	3	100%	R22, 90%
South Africa	16	1520.0	13%	3	90%	R507, 68%
China	16	1520.0	13%	3	100%	R717, 57%
Brazil	16	1520.0	13%	3	98%	R22, 90%
India	16	290.0	13%	3	100%	R134a, 70%
France	10	300.0	24%	1	20%	R404a, 66%
Mexico	25	1414.2	13%	3	90%	R22, 60%
Turkey	16	1520.0	17%	3	90%	R410A, 70%
Kenya	16	210.0	13%	3	100%	R22, 90%
Australia	15	300.3	12%	1	95%	R404A, 80%
Egypt	15	1520.0	13%	3	90%	R507, 68%
Ghana	/	/	/	/	/	/
Lebanon	/	/	/	/	/	/
Grenada	16	5.9	25%	3	85%	R404a, 74%
Moldova	16	150	25%	3	50%	R600A, 45%
Poland	16	75.0	24%	1	20%	R410A, 70%
Generic A5	16	230.0	13%	3	62.5%	R22, 90%

* CLASP has additional data available for India, China, and Indonesia; this information is confidential but will be incorporated into the final version of the model.

** CLASP also has updated data for domestic ACs in South Africa, Ghana, Egypt and Kenya from our 2020 Environmentally Harmful Dumping of Inefficient and Obsolete Air

Conditioners in Africa report. Due to time constraints this data was not included in this report but will be in the final model.

*** For both South Africa and Japan, the same inputs are used for Residential ACs and Residential Heat Pumps. That is because the same appliance provides both heating and cooling functions. The model counts emissions from both heating and cooling (i.e., input same values for both appliances, but we were careful to avoid double counting emissions when summing).

Important clarifications on inputs used:

- t_EOL values are all estimates based on manufacturer recommendations and judgment calls on realistic servicing rates in A5 and Non-A5 countries. We are currently using P.97 of the following European Commission report to estimate servicing for Non-A5 products. However, there are limitations in applying these values to estimate servicing rates of appliances in A5 countries (we would expect less frequent service in A5 countries).
- Certain countries have different leakage rates and average charges based on the various refrigerants used in each appliance. For the sake of conserving space, only a single value is included in this table, but a weighted average based on the share of each refrigerant is used in the model.
    - Values that were given in ranges (e.g., refrigerant charge, leakage rates) were averaged using a geometric mean so the model can output a single value. A geometric mean was used instead of an arithmetic mean to account for wide value ranges.

Model Inputs

- m = refrigerant charge
- L_{annual} = leakage rate
- GWP = global warming potential of refrigerant
- t_EOL = Number of years prior to EOL with no "top-off" refrigerant added to replace full charge
- αEOL = % lost at the EOL (1 - recycling factor)
- n = average lifetime
    - Note: in this model this value is an average/mean lifetime, however, in Mepsy the operating life follows a Weibull distribution, with some units failing earlier and some later

Key Outputs

The model produces several key outputs that are ultimately used to sum the total emissions in tonnes CO_2e from the refrigerants over each appliance's respective lifetime under the BAU scenario. The first calculation is the percentage of refrigerant charge lost during the lifetime. This is calculated by multiplying the average annual leakage rate (L_{annual}) by the appliance lifetime (n) and summing it with end-of-life recycling factor (α_{EOL}) multiplied by the amount of refrigerant remaining given the number of years prior to end of life that the refrigerant had not been recharged ($1 - L_{annual} * t\_EOL$)

Percentage of refrigerant charge lost during lifetime:

$$(L_{annual} * n) + \alpha_{EOL} * (1 - L_{annual} * t\_EOL)$$

From this calculation, the mass of refrigerant lost during the appliance lifetime is calculated by multiplying the percentage of refrigerant charge lost during lifetime ($(L_{annual} * n) + \alpha_{EOL} * (1 - L_{annual} * t\_EOL)$) by the refrigerant charge (m).

Mass of refrigerant lost during lifetime:

$$m * [(L_{annual} * n) + \alpha_{EOL} * (1 - L_{annual} * t\_EOL)]$$

> Note: in the model, the annual leakage and end-of-life leakage are tracked separately as they apply to different populations (the entire stock of products and the products retiring in the given year, respectively). They are also subject to different policy scenarios (ex: refrigerant transition versus EOL refrigerant recycling).
>
> Also, the impacts of each refrigerant are multiplied by the refrigerant mix for that country and appliance to calculate a national impact.

The annual leakage rate in tonnes CO_2e can be further supplemented with a parameter to reflect leakage during servicing. It is then calculated by multiplying the total refrigerant leakage ($m * L_{annual} + m$) by the lifetime and refrigerant GWP.

Annual leakage with additional service leakage (tonnes CO_2e):

$$(m * L_{annual} + m) * n * GWP$$

The end-of-life leakage is calculated separately. To get this value, the initial refrigerant charge (m) is reduced by the remaining amount of refrigerant charge at the end of life ($m * L_{annual} * t\_EOL$) and multiplied by the refrigerant recycling factor (α_{EOL}) and refrigerant GWP.

End of Life (EOL) leakage (tonnes CO2e):

$$m * (1 - L_{annual} * t\_EOL) * \alpha_{EOL} * GWP$$

Total annual emissions for domestic ACs and commercial refrigeration were cross-checked with the outputs from GIZ's Green Cooling Initiative data. Comparison of results for our model's residential AC emissions vs GIZ's unitary AC direct emissions from the year 2020 onward are below. Most of the countries show a good match between our findings and those of GIZ, with the exception of the UK, Germany, and India.[2]

In the UK and Germany, the discrepancy seems to be caused by the dominance of portable ACs, which were excluded from our stock numbers but seem to have been included in GIZ's, leading to lower emissions in our case.

[2] The refrigerant data and stock inputs used by GIZ are from the year 2018-2019 according to an interview with Irene Papst, GIZ consultant, on 11/03/2020. The CLASP model inputs for refrigerant data range from 2017-2020 and shipment estimates that were used to calculate stock values are for the year 2020.

MODEL RESULTS (BAU SCENARIO)

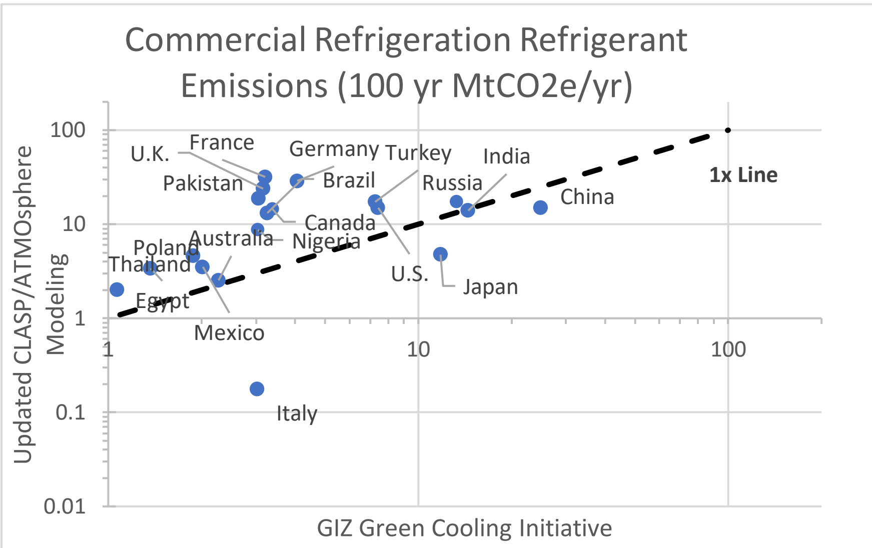
The 20- and 100-year annual GHG emissions for each country and appliance are shown in the tables below

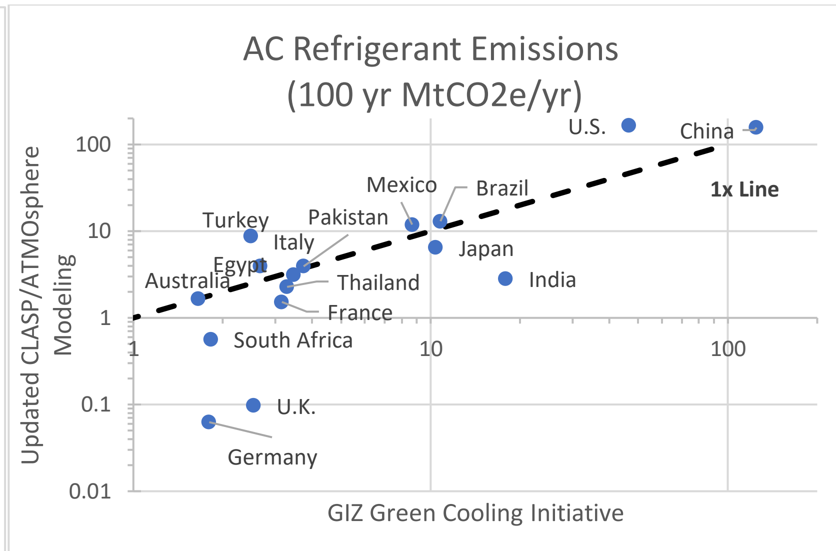
COUNTRY	RESIDENTIAL-SCALE AIR CONDITIONERS		RESIDENTIAL-SCALE HEAT PUMPS		RESIDENTIAL HEAT PUMP WATER HEATERS		PLUG-INS		CONDENSING		CENTRALIZED		TOTAL	
	100-yr Mt CO_2e	20-yr Mt CO_2e	100-yr Mt CO_2e	20-yr Mt CO_2e	100-yr Mt CO_2e	20-yr Mt CO_2e	100-yr Mt CO_2e	20-yr Mt CO_2e	100-yr Mt CO_2e	20-yr Mt CO_2e	100-yr Mt CO_2e	20-yr Mt CO_2e	100-yr Mt CO_2e	20-yr Mt CO_2e
Australia	2	4	0	0	0	0	0	0	2	3	3	6	7	13
Brazil	12	34	0	0	0	0	0	0	0	1	12	32	25	66
China	157	354	115	263	4	12	0	1	1	3	12	32	289	665
Egypt	4	9	0	0	0	0	0	0	0	1	3	5	7	14
France	1	2	5	11	0	0	0	0	2	3	30	40	38	56
Germany	0.1	0.1	2	4	0	0	0	0	2	3	27	34	30	42
India	3	8	0	0	0	0	0	0	1	2	12	21	16	31
Italy	2	5	2	3	0	0	1	3	1	2	0	0	6	13
Japan	6	19	1	4	0	0	1	1	13	20	0	0	21	45
Kenya	1	2	0	0	0	0	0	0	1	2	7	19	9	23
Mexico	9	26	0	0	0	0	0	0	2	3	2	4	12	33
Pakistan	4	11	11	28	0	0	0	0	1	2	17	44	33	85
Poland	0.1	0.2	0	0	0	0	0	0	1	2	4	8	5	10
South Africa	1	1	1	2	0	0	0	0	0	1	3	5	5	9
Thailand	2	5	0	0	0	0	0	0	6	11	0	0	9	17
Turkey	5	11	6	13	0	0	0	0	2	5	14	31	27	59
U.K.	0.1	0	8	18	0	0	0	0	3	4	21	33	32	56
U.S.	133	279	134	282	0	0	0	1	13	23	2	3	281	588
Grand Total	341	771	285	627	4	12	4	8	50	91	168	316	852	1825

Validating Results

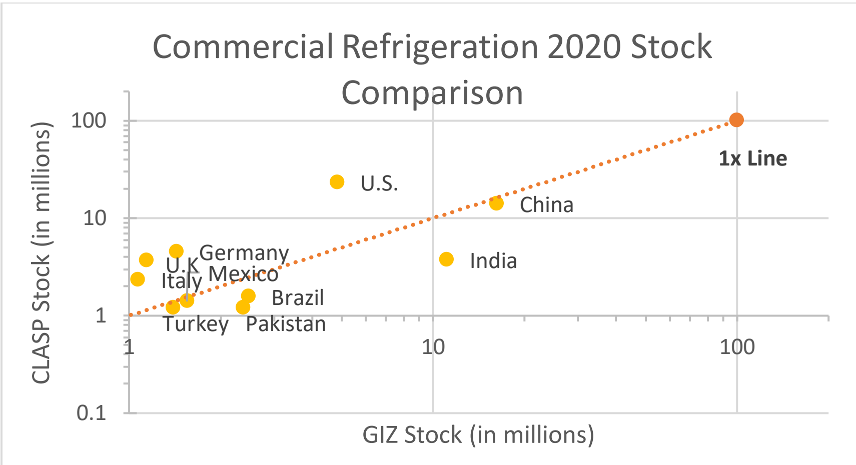
Total annual emissions for domestic ACs and commercial refrigeration were cross-checked with the outputs from [GIZ's Green Cooling Initiative data.] Comparison of results for our model's residential AC and commercial refrigeration emissions vs GIZ's unitary AC and commercial refrigeration direct emissions from the year 2020 onward are below.

Note: GIZ did not publish emissions from heat pumps or heat pump water heaters.





Our results for commercial refrigeration differ from GIZ's, which again, may partly be due to a difference in 2020 stock inputs.[3] Below is a scatter plot that compares the stock values per country.



[3] Our stock inputs for commercial refrigeration are based on a combination of data provided by Grand View Research as well as country level reports sourced by ATMOsphere.

Analysis of BAU Results

	Residential ACs	Residential Heat Pumps	Residential Heat Pump Water Heaters	Plug-ins	Condensing units	Centralized
Australia	3.92	0	0	0.03	2.59	6.03
Brazil	33.67	0	0	0.1	0.77	31.65
China	353.86	262.98	11.67	0.93	3.41	31.74
Egypt	9.07	0	0	0.03	0.58	4.74
France	1.83	11.05	0.49	0.38	2.79	39.7
Germany	0.13	3.88	0.02	0.1	3.47	34.05
India	8.11	0	0	0.2	2.26	20.53
Italy	4.79	3.39	0.14	2.84	1.55	0.2
Japan	19.38	4.1	0	1.45	20.23	0
Kenya	1.92	0	0	0.03	1.76	19.24
Mexico	25.88	0	0	0.26	3.24	3.96
Pakistan	11.21	27.64	0	0.01	1.75	44.43
Poland	0.24	0	0	0.01	2.01	7.79
South Africa	1.32	2.1	0	0	0.76	4.74
Thailand	5.23	0	0	0.28	11.05	0
Turkey	10.6	12.71	0	0.01	5.42	30.74
United Kingdom	0.2	17.58	0	0.25	4.48	33.25
United States	279.4	281.84	0.1	0.64	22.76	3.16

20-year GWP

	Residential ACs	Residential Heat Pumps	Residential Heat Pump Water Heaters	Plug-ins	Condensing units	Centralized
Australia	1.66	0	0	0.01	2.1	3.35
Brazil	12.3	0	0	0.05	0.29	11.92
China	156.57	114.71	3.98	0.49	1.26	11.96
Egypt	3.87	0	0	0.01	0.35	3.04
France	0.88	5.22	0.23	0.16	1.89	29.77
Germany	0.06	1.8	0.01	0.03	1.62	26.71
India	2.83	0	0	0.09	0.99	11.89
Italy	2.15	1.52	0.07	1.27	0.7	0.09
Japan	6.39	1.36	0	0.91	12.76	0
Kenya	0.83	0	0	0.02	0.66	7.25
Mexico	8.89	0	0	0.09	1.55	1.89
Pakistan	3.93	11.46	0	0.01	0.66	16.74
Poland	0.11	0	0	0	0.9	3.51
South Africa	0.55	0.85	0	0	0.46	3.04
Thailand	2.26	0	0	0.19	6.34	0
Turkey	5.04	6.05	0	0	2.44	13.85
United Kingdom	0.1	8.29	0	0.1	2.79	20.92
United States	132.54	133.7	0.04	0.36	12.71	1.83

100-year GWP

Note: values of zero are due to a lack of data and/or market in for that product in the respective country. Refer to the input tables above for clarifications.

Our results show that emissions from refrigerants account for 13 to 29% of the CO_2 emitted while powering seven common appliances in the countries examined. This significant percentage highlights the emissions savings potential to be had from implementing refrigerant regulations and cut-back policies.

100-year GWP: Residential ACs

100-year GWP: Residential Heat Pumps

The countries that have the highest emissions from refrigerants are the United States and China, most notably from the residential AC and residential heat pump sectors. A 2020 report published by CEMAC found that China has aggressively expanded their production of conventional refrigerants for domestic use as well as export starting in the year 2010.[4]

[4] Booten, C., et al. (2020). Refrigerants: Market Trends and Supply Chain Assessment. CEMAC. https://www.nrel.gov/docs/fy20osti/70207.pdf.

As global temperatures continue to rise and developing countries become more affluent, the consumption of air conditioning and refrigeration is bound to rise along with the emissions from their respective refrigerant use.

Next Steps / Future Projections

The next steps will be to integrate future policy scenarios and their respective impact on emissions into the model. The first policy scenario that will be considered is the 2016 Kigali Amendment. In order to model future emissions outputs, all countries will be broken into the following categories:

- Those that ratified the 2016 Kigali Amendment, and those that have not; countries that have not accepted the Kigali Amendment will nonetheless be expected to follow the least ambitious Kigali timeline due to the inevitable decrease in market availability of certain HFCs since Kigali limits both production and sales.
- The Kigali amendment countries will be further broken down into Article 5 (A5)/Non-article 5 (Non-A5), which follow different transition timelines:

	Non-A5 (developed countries)	A5 (developing countries) Group 1	A5 (developing countries) Group
Baseline HFC component	2011-2013 (average consumption)	2020-2022 (average consumption)	2024-2026 (average consumption)
Baseline HCFC component	15% of baseline	65% of baseline	65% of baseline
Freeze	-	2024	2028
1st step	2019 - 10%	2029 - 10%	2032 - 10%
2nd step	2024 - 40%	2035 - 30%	2037 - 20%
3rd step	2029 - 70%	2040 - 50%	2042 - 30%
4th step	2034 - 80%	-	-
Plateau	2036 - 85%	2045 - 80%	2047 - 85%
Notes	Belarus, Russian Federation, Kazakhstan, Tajikistan, Uzbekistan, 25% HCFC component and 1st two steps are later: 5% in 2020, 35% in 2025	Article 5 countries not part of Group 2	GCC (Saudi Arabia, Kuwait, United Arab Emirates, Qatar, Bahrain, Oman), India, Iran, Iraq, Pakistan

- Finally, any countries which research indicates are following their own timeline that is faster than that specified by the Kigali Amendment.

The tentative future policy groupings we will be using are outlined in the table below:

REGION	COUNTRIES	ARTICLE 5/ NON-ARTICLE 5	TRANSITION TIMELINE
South America	Argentina, Bolivia, Brazil, Chile, Colombia, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela	A5	A5
Central America	Belize, Costa Rica, El Salvador, Honduras, Guatemala, Nicaragua, Panama	A5	A5
Mexico	Mexico	A5	Freeze consumption in 2024 equal to 2020-2022 baseline; then A5
North America	Canada, United States	Non-A5	American Innovation & Manufacturing Act consistent with Non-A5 timeline
Caribbean	Antigua, Bahamas, Barbados, Cuba, Dominica, Dominican Republic, Grenada, Haiti, Jamaica, Saint Lucia, St Kitts and Nevis, St Vincent, Trinidad and Tobago	A5	A5
Egypt	Egypt	A5	A5
Southern Africa	Botswana, Lesotho, Namibia, South Africa, Swaziland	A5	A5
Western Africa	Benin, Burkina Faso, Cape Verde, Côte d'Ivoire, Equatorial Guinea, Gambia, Ghana, Guinea, Mali, Guinea-Bissau, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo	A5	A5
Other African Countries	Algeria, Angola, Cameroon, Central African Republic, Chad, Congo, Congo, Dem. Rep. of the, Gabon, Liberia, Libyan Arab, Jamahiriya, Morocco, Sao Tome,	A5	A5

REGION	COUNTRIES	ARTICLE 5/ NON-ARTICLE 5	TRANSITION TIMELINE
	Seychelles, Somalia, Sudan, Tunisia, Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Tanzania, U. Rep. of, Uganda, Zambia, Zimbabwe		
Turkey	Turkey	A5	A5
Lebanon	Lebanon	A5	A5
Israel	Israel	Non-A5	Non-A5
Western Asia	Bahrain, Qatar, Saudi Arabia, Oman, Kuwait, United Arab Emirates	A5	A5 Group 2
Central Asia	Tajikistan, Uzbekistan, Kazakhstan	Non-A5	Delayed Non-A5
Central Asia	Afghanistan, Armenia, Georgia, Iraq, Jordan, Kyrgyzstan, Syrian Arab Republic, Turkmenistan, Yemen, Azerbaijan,	A5	A5
Southern Asia	Bangladesh, Bhutan, Maldives, Sri Lanka, Nepal, Myanmar	A5	A5
Southern Asia	India, Iran, Islamic Rep. of, Pakistan	A5	A5 Group 2
Eastern Asia	Hong Kong, China (SAR)	Non-A5	Non-A5
Eastern Asia	China, Korea, Rep. of, Macau, Mongolia, North Korea	A5	A5
Eastern Asia	Japan	Non-A5	Faster than Non-A5 timeline
Southeastern Asia	Brunei Darussalam, Cambodia, Indonesia, Lao People's Dem. Rep., Malaysia, Thailand, Philippines, Singapore, Viet Nam	A5	A5
Oceania	New Zealand	Non-A5	Non-A5

REGION	COUNTRIES	ARTICLE 5/ NON-ARTICLE 5	TRANSITION TIMELINE
Oceania	Australia	Non-A5	Faster than Non-A5 timeline at first, with steps every 2 years
Oceania	French Polynesia	Non-A5	Non-A5
Oceania	Cook Islands, Fiji, Kiribati, Marshall, Micronesia, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu	A5	A5
EU 27	Finland, Greece, Monaco,	Non-A5	EU F-gas regulation, then Non-A5
	France	Non-A5	20% below EU F-gas regulation
	Austria, Luxembourg, Netherlands, Sweden, Switzerland, Belgium, Germany, Denmark	Non-A5	EU F-gas regulation, then Non-A5
	Italy, Portugal, Spain,	Non-A5	EU F-gas regulation, then Non-A5
	Other EU: Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia	Non-A5	EU F-gas regulation, then Non-A5
	Norway	Non-A5	EU F-gas regulation, then Non-A5
UK & Ireland	United Kingdom, Ireland	Non-A5	EU F-gas regulation, then Non-A5
Other Europe	Andorra, Iceland, Lichtenstein, Ukraine,	Non-A5	Non-A5

REGION	COUNTRIES	ARTICLE 5/ NON-ARTICLE 5	TRANSITION TIMELINE
Other Europe	Belarus, Russian Federation	Non-A5	Delayed Non-A5
Other Europe	Albania, Bosnia and Herzegovina, Croatia, Moldova, Rep. of, Montenegro, Serbia, Macedonia, TFYR	A5	A5

In order to incorporate the reduction in HFCs/emissions resulting from the Kigali targets into our baseline model, we will be using a vintaging table to calculate changes in appliance stocks and refrigerant GWPs over time using a similar approach to the EPA's Vintaging Model of ODS Substitutes.

As the Kigali Amendment targets take effect, the total GWP of the refrigerant used shall be frozen and then reduced in successive steps. The percentage reductions required to meet the Amendment vary across the six appliances based on their price sensitivity and availability of low-GWP alternative refrigerants.