HUM-471 Economic growth and sustainability June 4, 2024

Cool Choices in a Heating World

The Challenges of the Cooling industry: from Ozone Depleting to Climate Warming Refrigerants

Photo by Aleksander Pasaric 2024

Joshua Cohen-Dumani
Elisa Billard
Zaid Alhaj Kaddour
Kelan Solomon

Professor: Prof. Philippe Thalmann
Supervisor: Abdurahman Alsulaiman

This report first presents a historical view of ozone depletion and global warming with a focus on the cooling industry. Through the analysis of the past environmental impact of refrigerants with an IPAT equation, we extract the levers that were pulled to reduce the emissions of Ozone Depleting Substances. We show that after the enforcement of the Montreal Protocol regulating ODS, ozone depleting refrigerants are substituted by climate warming refrigerants, now regulated by the Kigali Amendment. Taking a step back on the total emissions of the cooling sector, we propose a second IPAT equation taking into account the second scope (electricity usage). Through this analysis we conclude that in order to meet the goals of the Global Cooling Pledge set by the COP28, we need to not only change the refrigerants we use, but as well improve the grid carbon intensity of the electricity and reduce the cooling demand per capita. We highlight the limitations of our IPAT analyses, regarding the assumptions on the data, as well as the intrinsic simplification needed to build such equations.

Contents

List of Figures

List of Tables

Glossary

- **CFC** : Chlorofluorocarbon
- **COP**: Coefficient of Performance
- **GHG**: Greenhouse gases
- **GWP:** Global Warming Potential [CO_2 equivalent or $CO2_{eq}$]
- **HFC** : Hydrofluorocarbon
- **ODP:** Ozone Depleting Potential [$CFC11$ equivalent or $CFC11_{eq}$]
- **ODS**: Ozone Depleting Substance
- **RAHCP** : Refrigeration, Air-Conditioning, Heat Pumps
- **UN**: United Nations

1 Introduction

Cooling is a fundamental component of modern society. While often overlooked in daily discourse, cooling has enabled us to preserve food for longer, and transport it around the world, it has allowed us to maintain comfortable indoor climates in even the harshest climates, and enables key technological cogs of society, from manufacturing electronics to data centers, or even preserve vaccines in medical facilities. In many ways, cooling is one of the most important technologies that bring a "developing" country to being "developed". However, beneath the utility and importance of cooling lies an important challenge: refrigerants are significant polluters, and have historically been linked with one of the biggest environmental crises in our history: the hole in the ozone layer. They are also important sources of greenhouse gas emissions, and we are therefore interested in understanding the nuances of previous and ongoing proposed solutions. The Montreal Protocol, an international agreement regulating such substances, stands out as one of the most influential agreements in recent history.

In this report, we will dive into the complex history and future of the environmental impact of the cooling sector, with a focus on the Montreal Protocol and its legacy. We have structured our approach with three main research questions:

I. Was the Montreal Protocol a success, and where are we now?

II. How did the Montreal Protocol influence the environmental impact of cooling?

III. Can Kigali Compliance help us reach our climate goals?

In the first part of this report, we will explore the different mechanisms that the Montreal Protocol put in place. We will look at how the challenge that it tries to tackle has evolved through time, ending with an analysis of the current situation.

In the second part, we will zoom in on the case of the cooling sector, which is inextricably linked with the Montreal Protocol, the hole in the ozone layer and Chlorofluorocarbon (CFC) emissions, and the subsequent rise of Hydro-fluorocarbon (HFC) emissions. We will present our first IPAT model, which will analyse the impact of refrigerants over time, trying to understand the true impact of the Montreal Protocol from a data-centric approach.

In the final part, we will try to take a more holistic view, and see how we can reach the goals of the Global Cooling Pledge from COP28 (UNEP 2024), to reduce the emissions of the cooling sector as a whole. For this, we will introduce our second IPAT decomposition which will also take into account indirect emissions due to electricity consumption. We will then consider multiple scenarios to try and understand what it takes to reach the climate goals set out by the Global Cooling Pledge, and notably understand if compliance with the Kigali amendment is enough to achieve these goals.

2 30 years of Montreal Protocol: from ODS to HFC regulation

2.1 Scientific and Historical Context behind Ozone Depletion

To fully understand the importance of the Montreal Protocol, it is necessary to dive into the historical and scientific context surrounding it. The ozone layer is arguably Earth's greatest shield. Present in the stratosphere, it absorbs harmful ultraviolet B radiation from the sun, which can cause skin cancer and cataracts in humans, and disrupts nature, from plants to marine life, by damaging DNA (US EPA 2023). In the 1970s, the scientists Rowland and Molina theorized that human-made CFC gases can cause the depletion of stratospheric ozone, and therefore are Ozone Depleting Substances (ODS). They found that these gases decompose, which releases atoms of chlorine and chlorine monoxide that are individually able to destroy large numbers of ozone molecules. Their research (Molina and Rowland 1974), for which they later won a Nobel prize, initiated the investigation into the true effect of CFCs (Britannica 2024).

In 1985, a huge discovery was made: a hole in the ozone layer was forming around Antarctica, and data confirmed that the cause was unquestionably CFCs. NASA soon released images that were broadcast around the world and captured public attention. CFCs were present in a variety of widely used products, particularly in refrigerants (which were toxic and flammable before that). However, they had also seen widespread adoption across different sectors. In 1986, 1128 million kg of CFCs were emitted: 28% of which from propellants, 26% from blowing agents, 23% from refrigerants, and 21% from cleaning agents (Wuebbles 1992).

2.2 Ratification and Objectives of the Montreal Protocol

With the scientific evidence that CFCs were damaging the ozone layer, the nations were urged to control their use of CFCs. This led to the adoption, in 1985, of the Vienna Convention for the Protection of the Ozone Layer (UNEP Ozone Secretariat 2024c), which served 2 important purposes: first, promoting open communication between countries of humanity's impact on the ozone layer, and second, to provide a framework for a future CFC controlling protocol. The convention was followed in 1987 by the Montreal Protocol on Substances that Deplete the Ozone Layer. The Montreal Protocol is the first international environmental treaty to be universally endorsed by 198 nations of the world (UNEP Ozone Secretariat 2024b), highlighting the global urgency prevalent at that time.

An important part of the Montreal Protocol was that the ODS phase-out schedules differ between developed and developing countries. The period for developing countries to respect the protocol is slightly longer, owing to the fact that they have fewer technical and financial resources to comply with newly introduced regulations (UNEP Ozone Secretariat 2020). Figure 1 shows precisely how the Protocol times the phase-out of the different ODSs. So-called "A5 countries" are countries that are considered to be developing countries according to Article 5 of the Montreal Protocol, themselves divided into two priority groups (the list of countries can be consulted in Section B.1). Moreover, a Multilateral Fund was created in 1991 to provide financial and technical assistance to developing country parties to the Montreal Protocol (Environment 2018). Since its inception, the Multilateral Fund has supported over 8,600 projects including industrial conversion, technical assistance, training, and capacity building worth over USD 3.9 billion.

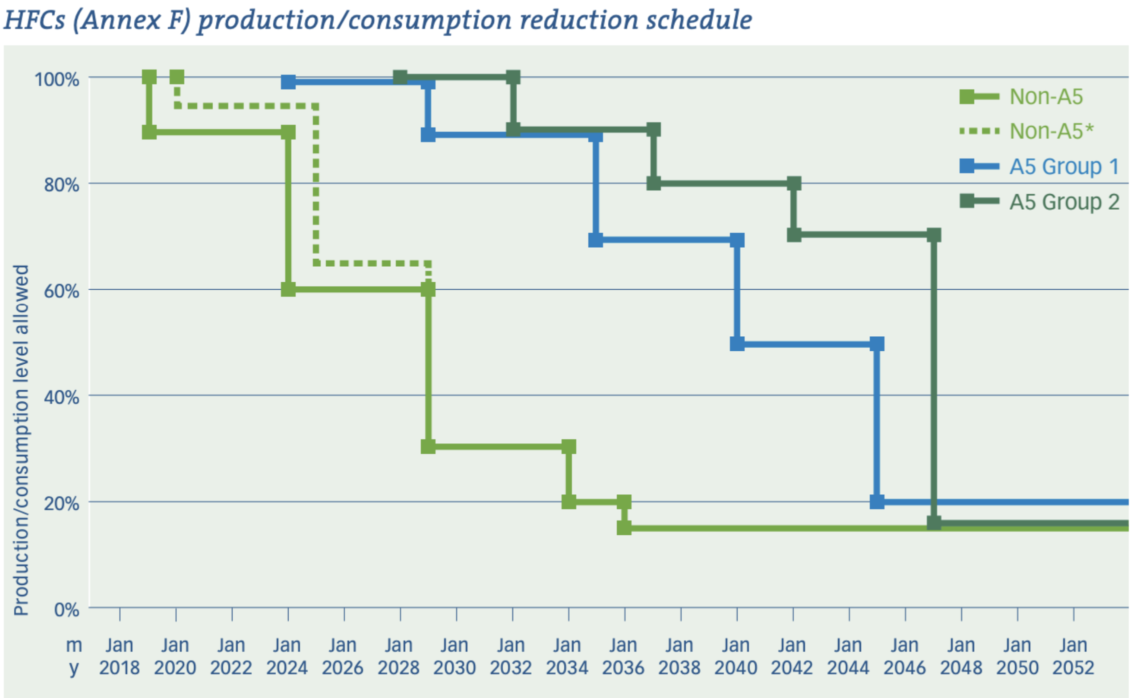


Figure 1: Phase-out of ODS according to the Montreal Protocol (UNEP Ozone Secretariat 2020)

2.3 The Replacement of CFCs with HFCs

As the Montreal Protocol came into effect, catalyzing a global policy shift, industries that heavily relied on ODS faced the urgent challenge of finding suitable substitutes. Most sectors were able to adapt over time. Propellants for example, which were responsible for around 69% of total CFC emissions in 1974, were able to bring down their contribution to 18% by 1992 (Wuebbles 1992). Aerosols and the cleaning industry also found alternatives like pump spays, compressed air propellants, and aqueous-based cleaning systems.

The timeline of different ODS emissions in the atmosphere and their abundance is depicted in Figure 2, where we see a huge decrease in emissions after the adoption of the Montreal Protocol, highlighting its success.

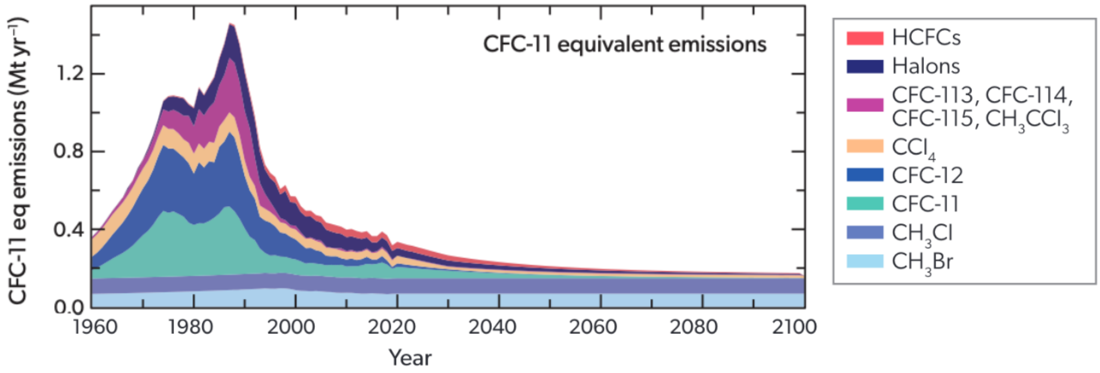


Figure 2: ODS emissions (top) and abundance in the atmosphere (bottom) (UNEP 2023c, p. 16)

However, not all solutions were sustainable and the refrigeration sector in particular faced a stern test. With no straightforward replacement, it transitioned from CFCs to HFCs. While HFCs are not ozone-depleting substances, they are a potent greenhouse gas, and as the cooling industry grew, the HFC emissions grew with it. This sector's struggle to adapt underscores a lingering challenge within industries heavily dependent on refrigerants, highlighting the complex balance between eliminating ODS and managing the unintended rise of greenhouse gases.

In the Figure 3 (based on data from (NOAA-CSL 2024, Figure ES-1) for ODSs and (UNEP 2023c, p. 135) for HFCs) , we can see the historical emissions of ODS and HFCs gases into the atmosphere, in which we can clearly see that the sharp decrease in ODS emissions were unfortunately followed by an important rise in HFC emissions (these emissions data will be further analysed in Section 3).

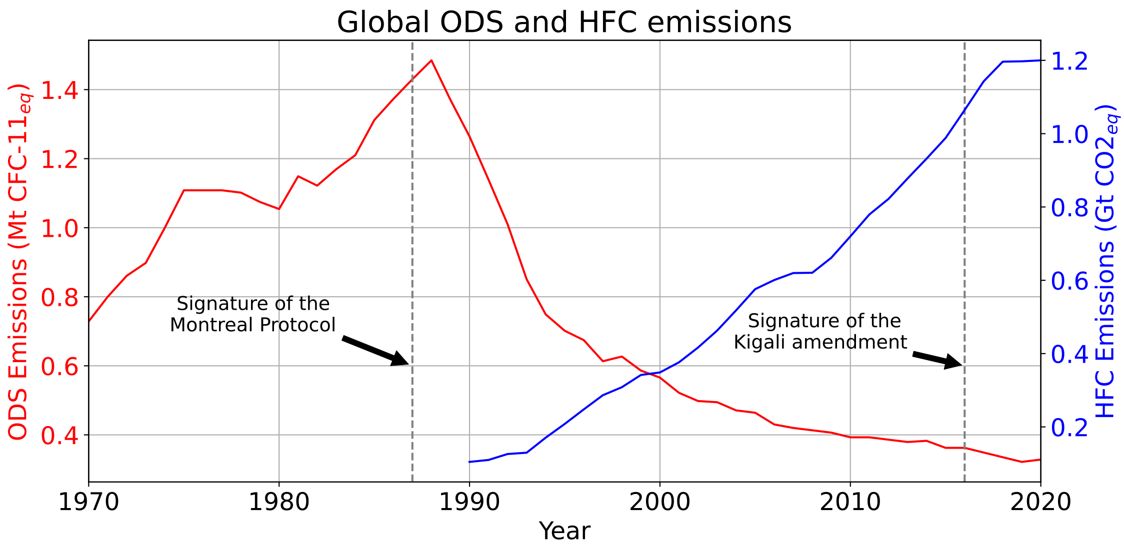


Figure 3: Historical emissions of ODS gases and HFC gases.

2.4 The Kigali Amendment on HFCs

The sharp increase in the usage of HFCs, initially because of their low Ozone Depletion Potential (ODP), has had unintended consequences. HFCs are among the gases with the highest Global Warming Potetntial (GWP), with some species reaching more than 10'000 times the GWP of CO_2 over 100 years in certain cases, putting them in the spotlight when the issue of climate change became a major topic worldwide. This realisation, combined with the projected massive growth in demand for cooling in developing countries over the next decades (as access to air conditioning and refrigeration spread further), led to the most important amendment in the Montreal Protocol's history. In 2016, one year after the COP21 in Paris, the Kigali amendment was added, whose goal is to phase out 85% of emissions of HFCs worldwide over the next 30 years.

The amendment plans for financing developing countries to help them reach these goals, as well as providing ambitious phase-down goals (by setting a 70% reduction of HFC emissions in 2029 for developed countries, for example). The details of the phase-out plan set out by the Kigali Amendment can be consulted in Section B.2. The mechanism follows a similar implementation as the initial Montreal Protocol (Figure 1).

As of today, 159 countries (UN 2024) have ratified the amendment, including most of the large emitters (namely, the United States, China, and India, which have all joined in 2021/2022). The success of the Kigali Amendment could be a huge stride toward credible sustainability and could be instrumental in helping reach the goals set out by the Paris Agreement.

2.5 Successes and Ongoing Challenges of the Montreal Protocol

Looking back after 30 years, can we consider the Montreal Protocol to be a real success? In a report published every four years on the progress of the Montreal Protocol, the panel confirmed the phase-out of nearly 99 per cent of banned ODS (UNEP 2023c). However, the Antarctic ozone hole still grew in size throughout the 1990s and the first decade of the 21st century. The first signs of recovery appeared in 2018. According to the World Meteorological Organization and the UNEP, the ozone layer is not expected to return to 1980 values until at least the mid-2030s over the Arctic and the 2060s over Antarctica (UNEP 2019). The explanation behind this long delay is that ODS stay in the atmosphere for many years and continue to cause damage after their emission.

The progress report (UNEP 2023c) showed that the Montreal Protocol has already benefited efforts to mitigate climate change, helping avoid global warming by an estimated 0.5°C (because gases which are ODS usually happen to be powerful greenhouse gases as well). The report also estimates that the Kigali Amendment will avoid another 0.3 to 0.5°C of warming by 2100 (UNEP 2023c, p. 4), showing that it has a substantial effect on the HFCs worldwide emissions.

Thus, the Montreal Protocol can widely be seen as one of the most successful treaties regulating a man-made impact on the environment. It avoided a global ozone catastrophe which would have had wide-ranging and disastrous effects, and has significantly reduced greenhouse gas emissions.

However, the Protocol has not finished playing its role, as the Kigali amendment has yet to demonstrate its effective regulation of Fluorinated gas emissions. Those emissions are mostly due to refrigerants, and account for about 2% of total worldwide emissions (US EPA 2016). This makes it an important factor to consider when thinking about possible solutions for climate change, ranking alongside sectors such as aviation, which accounts for roughly 2.5% (Ritchie and Roser 2024). The rest of the report will thus focus on cooling, with the aim of a better understanding the regulation of this key sector.

3 Influence of the Montreal Protocol on the cooling sector

As explained in Section 2.3, the cooling sector has been a significant ODS emitting sector and is currently responsible for most HFC emissions. According to (UNEP Ozone Secretariat 2015, p4), the RACHP sector (Refrigeration, Air-Conditioning, Heat Pumps) was responsible for 86% of HFC use in terms of GWP-weighted tonnes CO_2 equivalent. Out of these, 35% relate to refrigeration, 62% relate to air conditioning (cooling or "cooling & heating" units), and only 3% relate to "heating-only" heat pumps. We can therefore state that the broadly defined "cooling sector" is the most important HFC-emitting sector, which motivates our decision to further study it. To be specific, we define the "cooling sector" as the combination of the refrigeration sector (also commonly called the cold-chain sector) and the space cooling sector.

In the following subsections, we will start by looking at how refrigerant-related emissions of the cooling sector have evolved in quantity and nature through the past 50 years, by using IPAT equations as an analysis tool. Then, in Section 4 we will expand our IPAT equation to take into account indirect emissions due to energy usage, with the goal of predicting the evolution of the total emissions of the sector, based on different scenarios.

3.1 Theory: IPAT equation

The following general IPAT decomposition can be used to describe the emissions due to refrigerants:

$$\underbrace{I}_{\text{Emissions}} = \underbrace{P}_{\text{Population}} \times \underbrace{A}_{\substack{\text{Cooling}\\\text{demand}}} \times \underbrace{T}_{\substack{\text{Refrigerant}\\\text{emissions}\\\text{intensity}}} \tag{1}$$

Two equations with this structure will be used to study the emissions of ODS (Section 3.3.1) and those of HFC (Section 3.3.2).
The IPAT terms can be described as follows:

- The P term corresponds to the global population and is self-explanatory. It will be the same in both equations.
- The A term corresponds to $\frac{\text{Installed cooling capacity}}{\text{Population}}$ with $[\frac{W}{capita}]$ as a unit. It will also be the same in both equations.
- The T term will depend on the type of the particular emission that is considered in the equation. It takes this general form : $\frac{\text{Emissions}}{\text{Installed cooling capacity}}$

3.2 Data and Assumptions

To compute the time series of each term in the IPAT equations, we rely on the following data (the free web-tool automeris.io (Ankit 2024) is used to extract data from plots when necessary):

- Global population data for each year is taken from (UN 2022).
- To compute the A term, we use the time series for global installed cooling capacity that is given in (UNEP 2023b, p11). According to the source, this data is based on a complex model that estimates the installed cooling capacity in the world.
- ODS emissions data is taken from (NOAA-CSL 2024, Figure ES-1).
- HFC emissions data is taken from (UNEP 2023c, p. 135).

Furthermore, we will have to make the following assumptions:

- We use an exponential fit to predict the value of installed cooling capacity before the year 2000 (source data from (UNEP 2023b, p11) is only available starting that year). A fit with a yearly growth rate of +4.4 [%/year] is in excellent agreement with the source data. The fitted time series is plotted in Figure 4.

- Only data for global emissions for all sectors has been found. Therefore, to be able to do IPATs that only focus on the emissions of the cooling emissions, we must make an assumption: By assuming that the share of the cooling sector within the total emissions of given substances (ODS or HFC) is constant ($E_{cooling,yr=i} = E_{total,yr=i} \cdot \kappa$, with $\kappa = \text{cst}$, $g_\kappa = 0$), the growth of the emissions due to cooling become equal to the growth of total emissions:

$$(1 + g_{E_{cooling}}) = (1 + g_{E_{total}})(1 + g_\kappa)$$

$$g_{E_{cooling}} = g_{E_{total}}$$

  Also, if we normalize the emissions by their value at a given year (ie. 1970), we can use the following relation:

$$\frac{E_{cooling,yr=i}}{E_{cooling,yr=1970}} = \frac{E_{total,yr=i} \cdot \kappa}{E_{total,yr=1970} \cdot \kappa} = \frac{E_{total,yr=i}}{E_{total,yr=1970}}$$

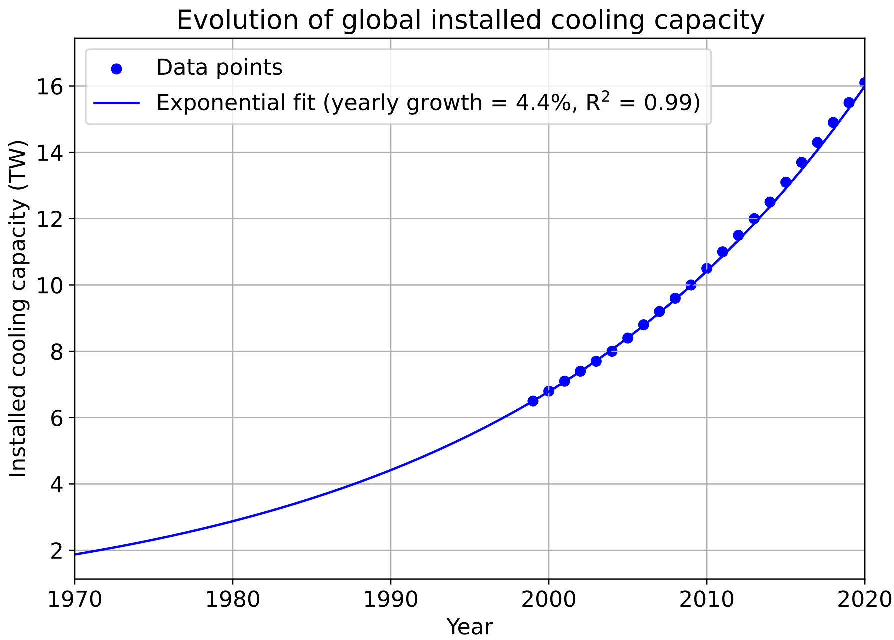


Figure 4: Evolution of installed cooling capacity in the world.

3.3 Analysis

3.3.1 IPAT with ODS emissions

Equation 1 can be specified to look at ODS emissions (measured in CFC-11 equivalent tons) as follows:

$$\underbrace{\text{ODS Emissions}}_{\text{[CFC-11 eq.]}} = \underbrace{\text{Population}}_{\text{[Capita]}} \times \underbrace{\frac{\text{Cooling capacity}}{\text{Population}}}_{\text{[TW/Capita]}} \times \underbrace{\frac{\text{ODS Emissions}}{\text{Cooling capacity}}}_{\text{[CFC-11 eq./TW]}}$$

Figure 5 plots the relative growth of all four terms of the IPAT decomposition by taking 1970 as a reference year.

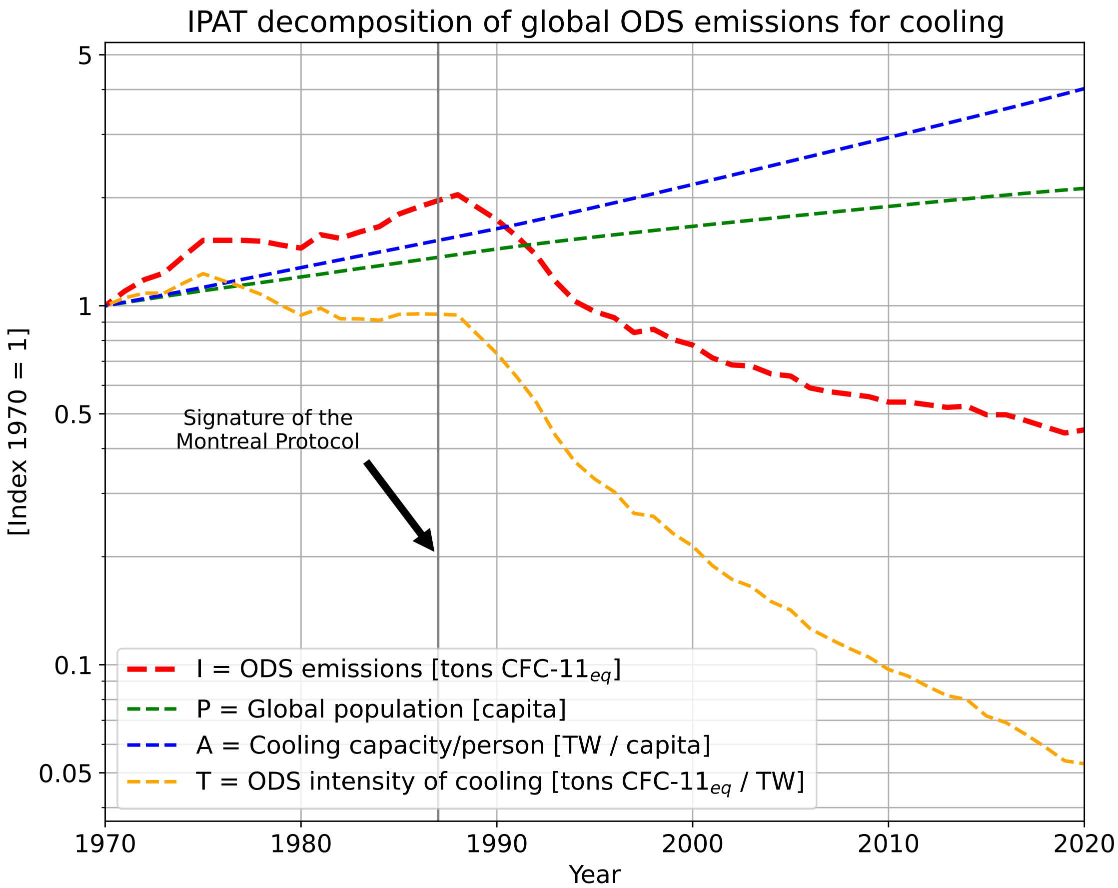


Figure 5: IPAT decomposition with I = ODS emissions

As one can expect, both the P and A terms have been increasing exponentially since 1970, and appear as straight lines given the log-scaled y-axis. In the 1970s, we observe an increase of the T term until 1975, followed by a decrease back to the 1970 level and a stagnation for almost 10 years. According to (Morisette 1989), this can be explained as follows: Following a 1974 report (Molina and Rowland 1974) confirming the link between ozone depletion and certain chemicals, countries including the U.S. and Canada started reducing the use of chlorofluorocarbons (CFCs) in aerosols. This initial national regulatory step slowed down in subsequent years mainly due to industry and political opposition, as well as revised scientific data indicating less severe ozone depletion than initially thought.

Stronger regulations arrived in 1988, following the international adoption of the Montreal Protocol. The T term started to decrease significantly and continuously, until today where it has reached 5% of its 1970 value. This sharp decrease of the T has allowed to achieve an impressive absolute decoupling: The I term is decreasing, despite that the P and A terms have never stopped increasing.

3.3.2 IPAT with HFC emissions

Equation 1 can be specified to look at HFC emissions (measured in CO_2 equivalent tons) as follows:

$$\underbrace{\text{HFC Emissions}}_{[\text{CO}_2\text{ eq.}]} = \underbrace{\text{Population}}_{[\text{Capita}]} \times \underbrace{\frac{\text{Cooling capacity}}{\text{Population}}}_{[\text{TW/Capita}]} \times \underbrace{\frac{\text{HFC Emissions}}{\text{Cooling capacity}}}_{[\text{CO}_2\text{ eq./TW}]}$$

Figure 6 plots the relative growth of all four terms of the IPAT decomposition by taking 1990 as a reference year.

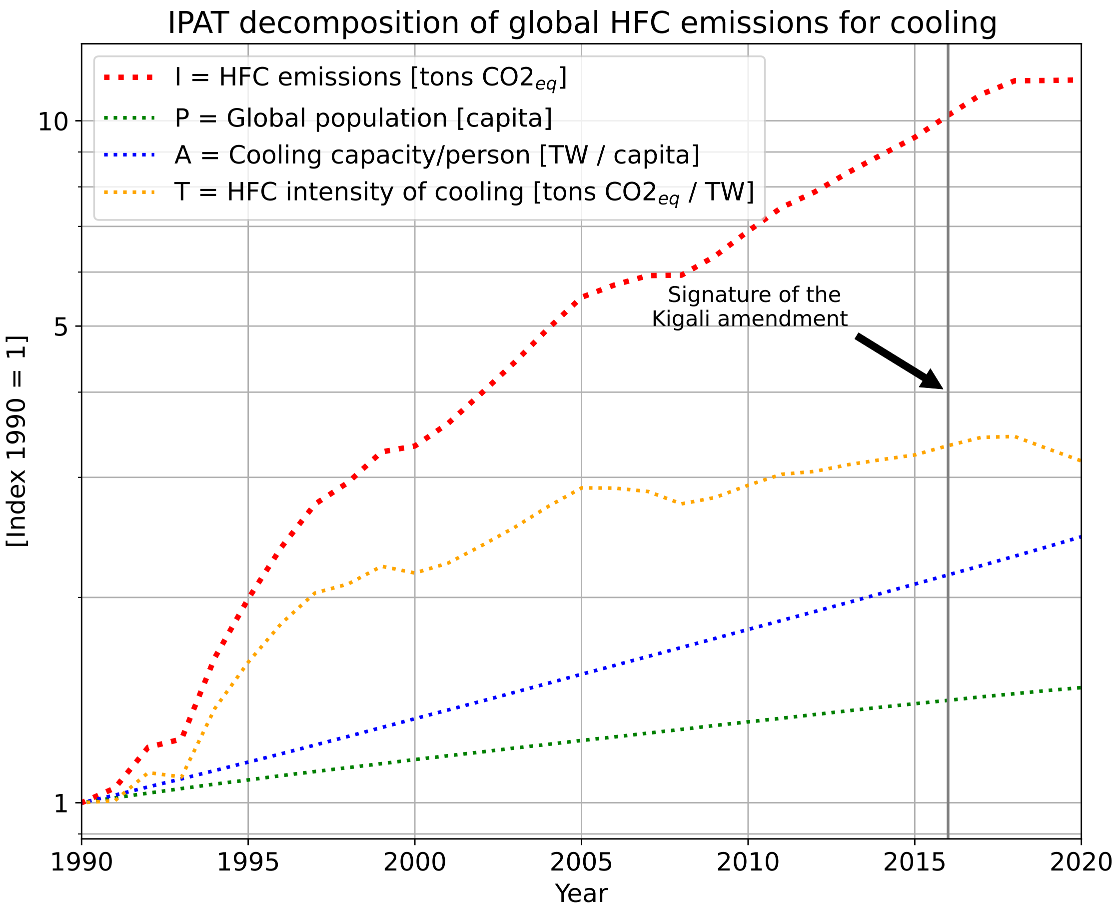


Figure 6: IPAT decomposition with I = HFC emissions

HFC coolants are primary substituents to the CFC coolants that the Montreal Protocol regulated. Their usage started in the 1990s, with their emissions data only being reported since then. We can observe a significant increase of the T term until 2015, which is the direct result of a gradual substitution of CFC-based coolants (which logically did not cause any HFC emissions). Following the signature of the Kigali amendment in 2016, we can see an inflexion in the T term, which is probably due to the regulations introduced by the amendment. However, because of the still increasing P and A term, the I term kept growing until the year 2017 and has been stagnating since, which can be described as relative decoupling.

3.4 Discussion

By looking at Figure 5, one can easily notice that the regulation of CFC coolants that was implemented thanks to the Montreal Protocol has been central to reducing ODS emissions and mitigating the Ozone hole problem. Furthermore, we can observe that only the technology lever seems to have been acted upon, and the decrease of ODS emissions is only due to the use of "cleaner" refrigerants (ODS-wise), and not to the reduction of the cooling capacity (ie. an increase in sobriety).

Based on these observations, one could be tempted to view the Montreal Protocol as an indisputable success and proof that absolute decoupling can be achieved thanks to technological changes. However, we can understand from Figure 6 that the decrease in the ODS intensity of coolants coincided with the increase in the HFC intensity of new coolants entering the market. Therefore, one could argue that the protocol simply replaces a negative impact with another. Of course, the impacts are different, and can not be directly compared against each other. But this shows the limit of the substitution approach: when replacing a negative substance with a new one, there's no guarantee that a new problem wouldn't arise with this new one. This aspect will be further discussed in Section 4.5.2, where we will go over the replacement of HFCs, and the potential risk that could arise with it.

One critique that could be done of the Montreal Protocol is that it didn't seem to have had a significant effect on the affluence lever (at least in the cooling sector). Whereas, if the affluence term would have decreased or slowed its growth, it would have allowed to decrease both impacts, instead of substituting one by another.

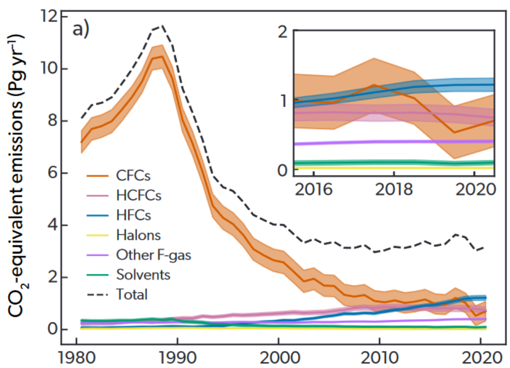
3.4.1 Model limitations and possible improvements

The IPAT equation that we have relied on in this analysis has allowed us to examine some global trends, but it has limitations that must be kept in mind. First of all, it relies on the strong assumption that the share of emissions due to cooling was constant through the years. This assumption remains to be proven and is probably an oversimplification. Furthermore, the equation shows the same weaknesses as most IPAT decompositions: by aggregating, diversity is lost. It doesn't allow us to study how the cooling demand is distributed among countries, nor does it take into account the cooling needs of different populations (some countries need more cooling because of global warming, whereas others could reduce their cooling demand with a sobriety approach). It also does not allow us to distinguish between different cooling types (refrigeration vs. space cooling), which rely on different technologies and might show different trends.

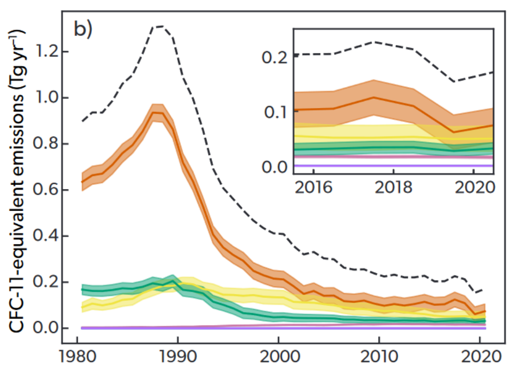
Finally, even if it is no secret that HFC coolants have replaced CFC coolants following the Montreal Protocol, the previous analysis has also allowed us to show the intrinsic limits of an IPAT decomposition: Given that the equation is only focused on a single impact, one must not forget the context. A decrease in the studied impact is not always synonymous with an overall improvement, as there might be an increase in another impact that is not captured in the equation.

3.4.2 Take-away on the Montreal Protocol

One must still be fair to the Montreal Protocol: This international agreement has put the international community on track to solve the ozone depletion problem and proved that countries could co-ordinate a global effort to solve a global environmental crisis. Yes, it has resulted in the replacement of CFCs by HFCs, which is far from being a perfect solution, but the disadvantage of HFC gases, which is their high GWP, must be put into perspective. Indeed, CFCs are **also** very potent GHG. Figure 7 from (UNEP 2023c, p. 72) allows us to get a better comprehension of the effect of the Montreal Protocol: The rapid regulation of the most destructive CFC molecules in the 90s has allowed to decrease both ozone depletion and global warming. Then, the gradual replacement of CFCs by HFCs has had a benefit for the ozone depletion problem, without either solving or degrading the global warming problem (given that CFCs and HFCs have similar GWP, the total effect remains constant).



(a) 100-year GWP-weighted (CO2-equivalent) emissions



(b) ODP-weighted (CFC-11-equivalent) emissions

Figure 7: Emissions of compounds regulated by the Montreal Protocol (UNEP 2023c, p. 72)

To summarize, the Montreal Protocol (excluding the Kigali amendment) has been key in fighting ozone depletion. It has provided a welcome reduction in ODS emissions during the 90s, and its impact on global warming after 2000 has been neutral.

4 Looking at the big picture: Reducing the total emissions of the cooling industry

Now that we have understood the limitations of the Montreal Protocol, we will expand our IPAT equation to take into account indirect emissions due to energy usage. The goal is to predict the evolution of the total emissions of the sector, based on different scenarios that will allow us to reach climate goals or not.

4.1 The Global Cooling Pledge

The Global Cooling Pledge, which has currently been signed by over 60 countries, is one of the key outcomes of the COP28, which was held in the UAE in 2023. It aims to “raise ambition and international cooperation through collective global targets to reduce cooling related emissions by 68% from today by 2050, significantly increase access to sustainable cooling by 2030, and increase the global average efficiency of new air conditioners by 50%” (UNEP 2024). While not legally binding, this pledge is a good first step toward decarbonising a key worldwide industry, and anticipating future problems that may arise as developing countries get better access to space cooling and refrigeration. Notably, it provides a strong framework for global cooperation and information sharing, meaning that it could act as the “Vienna Convention” to a future, binding protocol similar to the Montreal Protocol.

The main points outlined by the pledge are (UNEP 2023a, p. 2):

- Emissions reduction target: Reduction of total cooling-related emission by 68% globally, by 2050 relative to 2022 levels.
- Adoption of energy standards: Establishing Minimum Energy Performance Standards (MEPS) by 2030 to ensure new and refurbished buildings, as well as air conditioning equipment, to meet energy efficiency criteria.
- International cooperation: Promoting the use of the Multilateral Fund to help developing countries reach their goals, as well as pushing countries that have not yet ratified the Kigali amendment to do so.
- Annual review: Establishing a framework for annual progress reviews and engaging both subnational governments and non-state actors like the private sector to support and implement the pledge’s objectives.

4.2 The Refrigeration IPAT

Since the Global Cooling Pledge is a commitment to bring down **total** emissions by 68%, we have modified our IPAT to take into account the *direct* and *indirect* emissions. The direct emissions, as described in our first IPAT in Section 3.1, are the high GWP substances emitted and leaked by cooling equipment, measured in $CO2_{eq}$. The indirect emission, on the other hand, is the quantity of CO_2 released in the production of the electricity used to power the equipment. Both factors will play a crucial role in reducing overall emissions, giving us additional levers to pull in the effort to achieve the goal. These indirect emissions can be divided into a "performance" factor, which we have defined as the inverse of the coefficient of performance (COP^{-1}), a runtime in hours, that represents the average duration that each Watt of equipment is run for per year, and a carbon grid intensity, which is the amount of CO_2 released per kWh of electricity produced.

Therefore, the "technology" term corresponds to C for direct emissions and $E \times E \times G$ for indirect emissions. Our final IPAT can therefore be written as follows:

$$\underbrace{I}_{\text{Impact}} = \underbrace{P}_{\text{Population}} \times \underbrace{A}_{\substack{\text{Cooling}\\\text{demand}}} \times (\underbrace{C}_{\substack{\text{Refrigerant}\\\text{GWP intensity}}} + \underbrace{E}_{\text{COP}^{-1}} \times \underbrace{R}_{\substack{\text{Average}\\\text{Runtime}}} \times \underbrace{G}_{\substack{\text{Grid}\\\text{carbon}\\\text{intensity}}})$$

	Formula	Unit
I	CO_2 equivalent	$CO2_{eq}$
P	Population	cap
A	$\frac{\text{Cooling Capacity}}{\text{Population}}$	$\frac{W}{cap}$
C	$\frac{\text{Refrigerant GWP}}{\text{Cooling Capacity}}$	$\frac{CO2_{eq}}{W}$
E	$\frac{\text{Elec.power}}{\text{Cooling Capacity}}$	$\frac{W}{W}$
R	$\frac{\text{Elec. Consumption}}{\text{Elec. Power}}$	$\frac{Wh}{W}$
G	$\frac{\text{Elec. Production CO2}}{\text{Elec. Consumption}}$	$\frac{CO2}{Wh}$

Table 1: Refrigeration IPAT terms

$$CO2_{eq} = cap \times \frac{W}{cap} \times (\frac{CO2_{eq}}{W} + \frac{W}{W} \times \frac{Wh}{W} \times \frac{CO2}{Wh})$$

4.3 Data and Assumptions

We will be comparing our 2050 scenarios with 2022 data. We used the following 2022 values to calculate the different terms of our IPAT.

Pop[1]	8.1	[bn]
Cooling Capacity[2]	22	[TW]
Electric consumption	5000[3]	[TWh]
Indirect emissions[4]	2.6	[bn t $CO2$]
Direct emissions[5]	1.5	[bn t $CO2_{eq}$]
Energy intensity[6]	0.0005	[bn t $CO2/TWh$]
COP	1.5	-

We have also assumed the COP to be a constant 1.5 for all appliances, this is discussed in more detail in Section 4.5.1.

4.4 Analysis of different scenarios

For our **baseline scenario**, which we will call **Scenario 1** (or S1), we will be considering the following data in 2050. These numbers as well as the ones in the following scenarios have been inspired by the Global Cooling Watch (UNEP 2023b, pp. 8–26). They should not be taken as absolute predictions, but rather as global estimations useful to analyse the impact of each lever.

Pop [7]	9.7	[bn]
Cooling capacity	62	[TW]
Electric consumption	27778	[TWh]
Indirect emissions	7.5	[bn t $CO2$]
Direct emissions	1.5	[bn t $CO2_{eq}$]
Energy intensity	0.00027	[bn t $CO2/TWh$]
COP	1.5	-

This scenario represents the most likely outcome if no action is taken. As expected, the population, cooling capacity and electricity consumption for cooling have drastically increased: this has a large impact on the final emissions. The energy intensity has dropped due to the increasing popularity of PV and other green energy sources (IEA 2018, p. 66). We have considered the scenario where the COP remains unchanged, which can be viewed as a pessimistic outcome.

[2]United Nations 2024
[3]UNEP 2023b, p. 10
[4]UNEP 2023b, p. 22
[5]UNEP 2023b, p. 22
[6]Calculated from indirect emissions and Cooling Capacity
[7]United Nations 2024

As seen in Figure 8, our annual carbon emissions due to cooling will therefore be 9 billion tonnes of equivalent CO_2 by 2050 under this scenario, an increase of around +120% compared to 2022. A large proportion of the addition CO_2 is due to the rise in Cooling Demand (A) and Average Runtime (R) which are closely linked to an increased accessibility to cooling technology (due to economic improvements) and an increased use of cooling due to global warming.

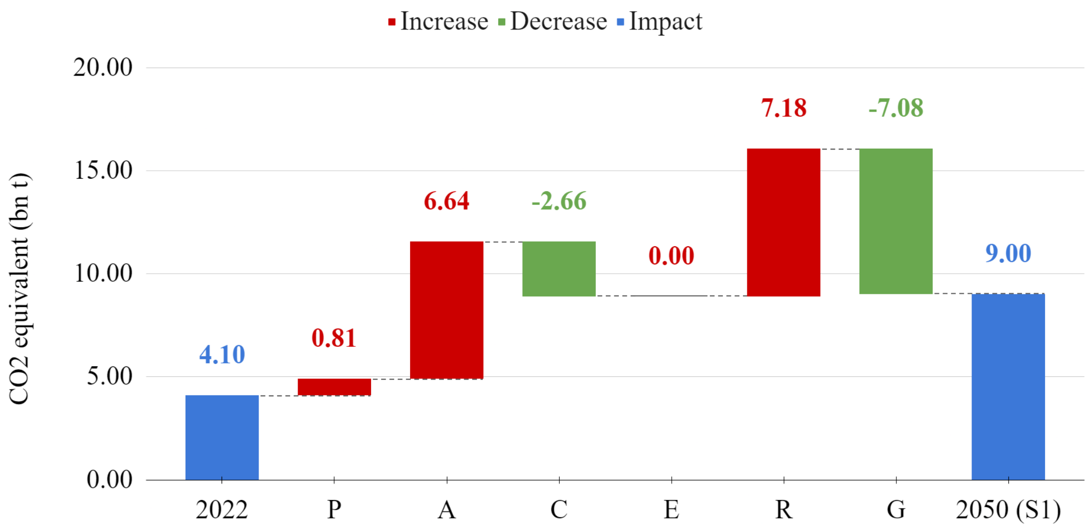


Figure 8: $CO2_{eq}$ produced by refrigeration in 2022 and 2050 (S1)

This baseline scenario is far from satisfying the Global Cooling Pledge. In the following scenarios, we will have a look at what could be done to achieve the -68% in global emissions required. All the scenarios are summarised in Table 2 and Figure 9.

Scenario 2 (or S2) is the **world Kigali compliant scenario**, meaning that every country signs and adheres to the amendment reducing the global consumption of HFCs by 80% by 2050. We have made the assumption that reducing HFC consumption by as much would reduce the direct emissions by the same amount, leaving us with 0.3 billion tonnes of equivalent CO_2. This reduction in direct emissions has the knock on effect of reducing the Refrigerant GWP intensity (C) by 92% in our IPAT. Unfortunately, this only reduces the impact (I) by 30%, or 1.2 billion tonnes of CO_2, still leaving us with a 90% increase by 2050. We can therefore state that the Kigali amendment is not sufficient by itself to reach the Global Cooling Pledge goals.

Scenario 3 (or S3) is a proposed scenario that would **meet the Global Cooling Pledge goals**. It's built upon the world Kigali Compliant scenario with additional action on the A, E, R and G levers. We can start by making the assumption that the COP will increase, meaning that the E lever will reduce the amount of CO_2 produced. In this scenario, we have estimated a 25% increase in COP by 2050. The Grid carbon intensity (G) will also have a strong impact, with the growing popularity and investment in green energy, we could imagine a large decrease by 2050. We can estimate, with global collaboration and large investments in developing countries, an intensity of 100 gCO2/kWh by 2050 (Enerdata 2024, IEA 2023). With global warming and economic improvements, inevitably, both the Cooling Capacity (which influences the Cooling Demand (A)) and Average Runtime (R) will increase. We can, however, mitigate this by practicing sobriety, mainly in developed countries where current cooling habits are rarely a necessity. In this scenario, we have imagined a 2050 Cooling Demand of 5 kW/capita and an Average Runtime of 440h (compared to 2.72 and 340 respectively in 2022). This results in 50% less Cooling Demand and 68% less runtime than in the 2050 baseline scenario (S1). The combination of all these measures allow us to nearly reach the -68% emissions reduction that is required by the Global Cooling Pledge.

	2022	2050		YoY gr.	Total gr.
Scenario 1					
(P) Population	8.10	9.70	[bn]	0.65%	19.75%
(A) Cooling Demand	2.72	6.39	$[\frac{kW}{cap}]$	3.10%	135.33%
(C) Refrigerant intensity	0.07	0.02	$[\frac{tCO2_{eq}}{kW}]$	-3.58%	-63.94%
(E) 1/COP	0.67	0.67	-	0.00%	0.00%
(R) Average Runtime	340.91	672.04	$[\frac{Wh}{W}]$	2.45%	97.13%
(G) Grid carbon intensity	5.2e-4	2.7e-4	$[\frac{tCO2}{kWh}]$	-2.35%	-48.55%
Scenario 2					
(C) Refrigerant intensity	0.07	0.005	$[\frac{tCO2_{eq}}{kW}]$	-9.02%	-92.90%
Scenario 3					
(A) Cooling Demand	2.72	5.00	$[\frac{kW}{cap}]$	2.20%	84.09%
(E) 1/COP	0.67	0.50	-	-1.02%	-25.00%
(R) Average Runtime	340.91	440.00	$[\frac{Wh}{W}]$	0.92%	29.07%
(G) Grid carbon intensity	5.2e-4	1e-4	$[\frac{tCO2}{kWh}]$	-5.75%	-80.95%
(I) Impact	**4.10**	**1.30**	[bn t]	**-4.02%**	**-68.34%**

Table 2: Impact of scenarios 1-3

4.5 Discussion

The combination of efforts that are put into Scenario 3 to comply with the Global Cooling Pledge underscores the complexity of the goal; substantial compromises will need to be made and sensitization of the public to the environmental effects of excessive cooling is paramount. Achieving this goal demands a collective effort, encompassing policy changes, technological advancements, and widespread behavioural shifts towards more sustainable cooling practices.

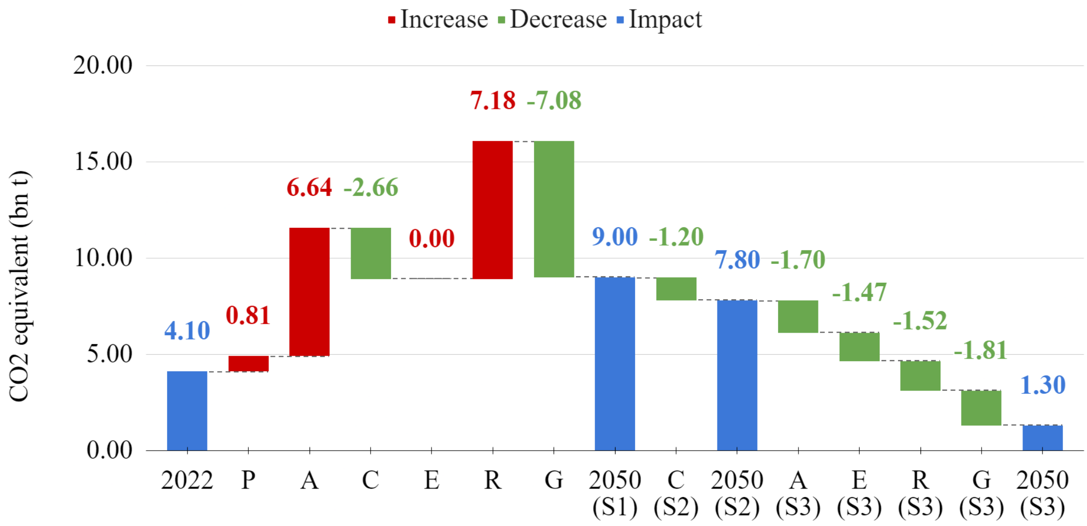


Figure 9: $CO2_{eq}$ produced by refrigeration in 2022 and 2050 (S1 - S3)

4.5.1 IPAT Limitations

The IPAT described in Section 4.2 has limitations due to how it is constructed and due to different assumptions that were made. Firstly, we cannot tell if the impact is reduced through substitution of the refrigerant: we could, for example, replace HFCs with a low GHP but high ODP substance, reducing the impact of our IPAT, but effectively shifting the problem elsewhere. Secondly, we could take into account other factors that affect the Cooling Demand and Average Runtime such as passive cooling measures and improved insulation. An increase in these terms would reduce the need for active cooling, reducing the overall impact. Finally, we have assumed a COP of 1.5. However, it's important to note that this figure can vary significantly depending on various factors, including environmental conditions, desired cooling levels, and the specific appliance being used. We used the data from the Global Cooling Watch (Global Cooling Watch 2024, p. 19) to estimate the average COP overall conditions and appliances. This is a crude estimate but illustrates the baseline scenario we are working with. Despite its simplicity, the percentage increase remains representative of the potential impact, providing a starting point for further analysis and refinement.

4.5.2 Replacement of HFCs

As seen throughout the report, most refrigerants currently in use are harmful to the environment, with some being thousands of times more polluting than CO_2. There are alternatives with lower environmental impact available, but there is no perfect and easy solution. These alternatives can significantly reduce greenhouse gas emissions caused by leaks or disposal. The transition to these safer refrigerants is already happening, but it could move faster with the right support systems in place. To accelerate the switch to environmentally friendly refrigerants, governments need to ensure that rules, standards, regulations, and training programs are in place. The most mature markets for these alternatives are residential cold chains and mobile air conditioning, followed by food retail and food service refrigeration (Global Cooling Watch 2024, p. 11). Here is a list of some of the main alternatives (EPA 2016, p. 4):

- **R-290 (Propane) and Hydrocarbon Blends (e.g. R-441A)**: Used in small AC units, however, there are safety concerns regarding flammability requiring trained technicians and can increase installation costs.
- **Carbon Dioxide (CO2, R-744)**: Employed in large AC equipment, especially ducted systems.
- **Ammonia (R-717)**: Suitable for chillers in various building AC applications and district cooling. Safety concerns that may increase installation costs and require technician training.
- **Water (R-718)**: Developmental chillers demonstrated, however, require large space and complex compressor technology.
- **HFC-32**: HFC with a lower GWP.
- **Low-GWP Fluorinated Compounds**: Various compounds like HFO-1234yf, HFO-1234ze(E), and Solstice™ 1233zd(E) are under development or in use in different types of chillers and AC equipment.
- **HFC/HFO Blends**: Various blends are being developed, such as R-450A and R-513A, for different types of AC equipment.

Challenges like accessibility, safety concerns, and environmental issues hinder the widespread adoption of these alternatives. Some areas lack access to low-GWP products, while high prices and outdated regulations slow down the transition. Additionally, because HFCs are regulated under the Kigali Amendment, their prices have risen in some places, leading to illegal trading (UNEP 2023b, p. 88).

Finally, investment in innovation is crucial for developing better cooling technologies. Various programs and funds support research and development in sustainable cooling, but more investment is needed to bring environment friendly products to market. Leading companies, like Daikin, Danfoss or Godrej are investing heavily in product development to address sustainability issues in cooling (UNEP 2023b, p. 96). Multilateral development banks can also play a significant role by integrating sustainable cooling into their financing strategies.

5 Conclusion

Throughout this report, we have engaged in a rigorous analysis of the cooling industry's role in environmental sustainability, with the help of IPATs. Our study has highlighted the success of the Montreal Protocol, its influence on the environmental impacts of cooling, and the effectiveness of Kigali Compliance in moving us towards our current climate objectives.

We have established that while the Montreal Protocol has been successful in phasing out ozone-depleting substances, the transition to high-global-warming-potential hydrofluorocarbons (HFCs) introduces new challenges that require ongoing attention and action. This transition underscores the critical need for adaptive management within international environmental governance. The projections in future cooling scenarios emphasise the importance of considering all the levers that affect refrigerants, cooling systems and electricity.

For future research, we propose a detailed, country-specific analysis to further dissect the variations in compliance and impact, differentiating between Article 5 and non-Article 5 countries. Such an analysis should consider the disparate cooling demands influenced by different stages of economic development and the varying impacts of global warming. Exploring the potential of emerging low-impact cooling technologies across diverse geographic and climatic conditions could provide valuable insights into more sustainable practices.

Reflecting on our collaborative experience, this project has not only broadened our understanding of complex environmental issues but also highlighted the limitations inherent in the IPAT model. Our team greatly benefited from the structured guidance of our teaching assistant, whose insights were crucial in navigating the complexities of environmental protocols.

In conclusion, the continuous evolution of international environmental agreements is essential to address the shifting landscape of global environmental challenges effectively. Enhanced by robust research and sustained by global cooperation, these efforts are vital for advancing towards the ambitious targets set by international climate commitments and ensuring a sustainable future for all.

References

Aleksander Pasaric (2024). *Photo by Aleksandar Pasaric on Pexels*. en-US. URL: https://www.pexels.com/photo/low-angle-shot-of-an-old-apartment-building-exterior-with-worn-out-paint-3164031/ (visited on 05/12/2024).

Ankit, Rohatgi (2024). *automeris.io*. URL: https://automeris.io/WebPlotDigitizer.html (visited on 05/10/2024).

Britannica (Mar. 2024). *F. Sherwood Rowland — Atmospheric Chemistry, Ozone Layer, Nobel Prize — Britannica*. en. URL: https://www.britannica.com/biography/Frank-Sherwood-Rowland (visited on 04/24/2024).

Enerdata (2024). *2050 Projections for CO2 Intensity of Electricity Generation*. en. URL: https://eneroutlook.enerdata.net/forecast-world-co2-intensity-of-electricity-generation.html (visited on 04/22/2024).

Environment, U. N. (Oct. 2018). *About Montreal Protocol*. en. URL: http://www.unep.org/ozonaction/who-we-are/about-montreal-protocol (visited on 05/03/2024).

EPA, US (2016). "TRANSITIONING TO LOW-GWP ALTERNATIVES in Residential and Commercial Air Conditioningand Chillers". en. In.

Global Cooling Watch, United Nations Environment (Mar. 2024). "Annexes - Global Cooling Watch 2023 - Keeping it Chill: How to Meet Cooling Demands while Cutting Emissions". English. In: URL: https://wedocs.unep.org/xmlui/handle/20.500.11822/45178 (visited on 05/05/2024).

IEA (2018). "The Future of Cooling". en. In.

— (July 2023). *CO2 emissions intensity of electricity generation in the Announced Pledges Scenario, 2022-2030*. en-GB. URL: https://www.iea.org/data-and-statistics/charts/co2-emissions-intensity-of-electricity-generation-in-the-announced-pledges-scenario-2022-2030 (visited on 05/11/2024).

Molina, Mario J. and F. S. Rowland (June 1974). *Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone*. en. Tech. rep., pp. 810–812. URL: https://www.nature.com/articles/249810a0 (visited on 04/24/2024).

Morisette, Peter M. (1989). *Evolution of Policy Responses to Stratospheric Ozone Depletion*. URL: http://www.ciesin.org/docs/003-006/003-006.html (visited on 05/06/2024).

NASA Ozone Watch (2024). *NASA Ozone Watch: Antarctic ozone maps for 1985-09*. URL: https://ozonewatch.gsfc.nasa.gov/monthly/monthly_1985-09_SH.html (visited on 05/15/2024).

NOAA-CSL (2024). *Scientific Assessment of Ozone Depletion 2022: Executive Summary*. en. URL: https://csl.noaa.gov/assessments/ozone/2022/executivesummary/ (visited on 05/06/2024).

NRDC (Aug. 2021). *India to Ratify the Kigali Amendment, Develop HFC Strategy*. en. URL: https://www.nrdc.org/bio/sameer-kwatra/india-ratify-kigali-amendment-develop-hfc-strategy (visited on 05/11/2024).

Ozone Secretariat (2024). *Article 5: Special situation of developing countries.* URL: https://ozone.unep.org/treaties/montreal-protocol/articles/article-5-special-situation-developing-countries (visited on 05/15/2024).

Ritchie, Hannah and Max Roser (Apr. 2024). "What share of global CO2 emissions come from aviation?" In: *Our World in Data.* URL: https://ourworldindata.org/global-aviation-emissions (visited on 05/11/2024).

UN (2022). *World Population Prospects - Population Division - United Nations.* URL: https://population.un.org/wpp/ (visited on 05/15/2024).

— (2024). *United Nations Treaty Collection.* EN. URL: https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-2-f&chapter=27&clang=_en (visited on 05/03/2024).

UNEP (Nov. 2019). *Thirty years on, what is the Montreal Protocol doing to protect the ozone?* en. Section: News and Stories. URL: http://www.unep.org/news-and-stories/story/thirty-years-what-montreal-protocol-doing-protect-ozone (visited on 05/01/2024).

— (Dec. 2023a). "Global Cooling Pledge for COP28". In: URL: https://wedocs.unep.org/20.500.11822/44310.

— (Dec. 2023b). *Keeping Cool in an Increasingly Hotter World: UNEP Spotlight.* en. United Nations Environment Programme. ISBN: 978-92-807-4106-3. DOI: 10.59117/20.500.11822/44243. URL: https://wedocs.unep.org/20.500.11822/44243 (visited on 04/22/2024).

— (Jan. 2023c). *Scientific Assessment of the Ozone Layer Depletion: 2022.* en. Section: publications. URL: http://www.unep.org/resources/publication/scientific-assessment-ozone-layer-depletion-2022 (visited on 04/21/2024).

— (2024). *Global Cooling Pledge.* en-US. URL: https://coolcoalition.org/global-cooling-pledge/ (visited on 05/03/2024).

UNEP Ozone Secretariat (2015). *Overview of HFC market sectors. Fact Sheet 2.* English. text. URL: https://iifiir.org/en/fridoc/overview-of-hfc-market-sectors-fact-sheet-2-30951 (visited on 05/05/2024).

— (2020). "Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer. Fourteenth edition (2020)". en. In.

— (2024a). *Classification of Parties — Ozone Secretariat.* URL: https://ozone.unep.org/classification-parties (visited on 05/15/2024).

— (2024b). *Ozone and You.* URL: https://ozone.unep.org/ozone-and-you#the-montreal (visited on 04/24/2024).

— (2024c). *The Vienna Convention for the Protection of the Ozone Layer — Ozone Secretariat.* URL: https://ozone.unep.org/treaties/vienna-convention (visited on 05/11/2024).

United Nations (2024). *Population.* en. Publisher: United Nations. URL: https://www.un.org/en/global-issues/population (visited on 05/02/2024).

US EPA, OAR (Jan. 2016). *Global Greenhouse Gas Overview.* en. Overviews and Factsheets. URL: https://www.epa.gov/ghgemissions/global-greenhouse-gas-overview (visited on 05/11/2024).

— (Dec. 2023). *Information on Ozone and Ozone Depletion.* en. Overviews and Factsheets. URL: https://www.epa.gov/ozone-layer-protection/information-ozone-and-ozone-depletion (visited on 04/24/2024).

Wuebbles, D.J. (1992). *The role of refrigerants in climate change*. Tech. rep. United States, p. 21.

A Appendix: Images of the ozone hole

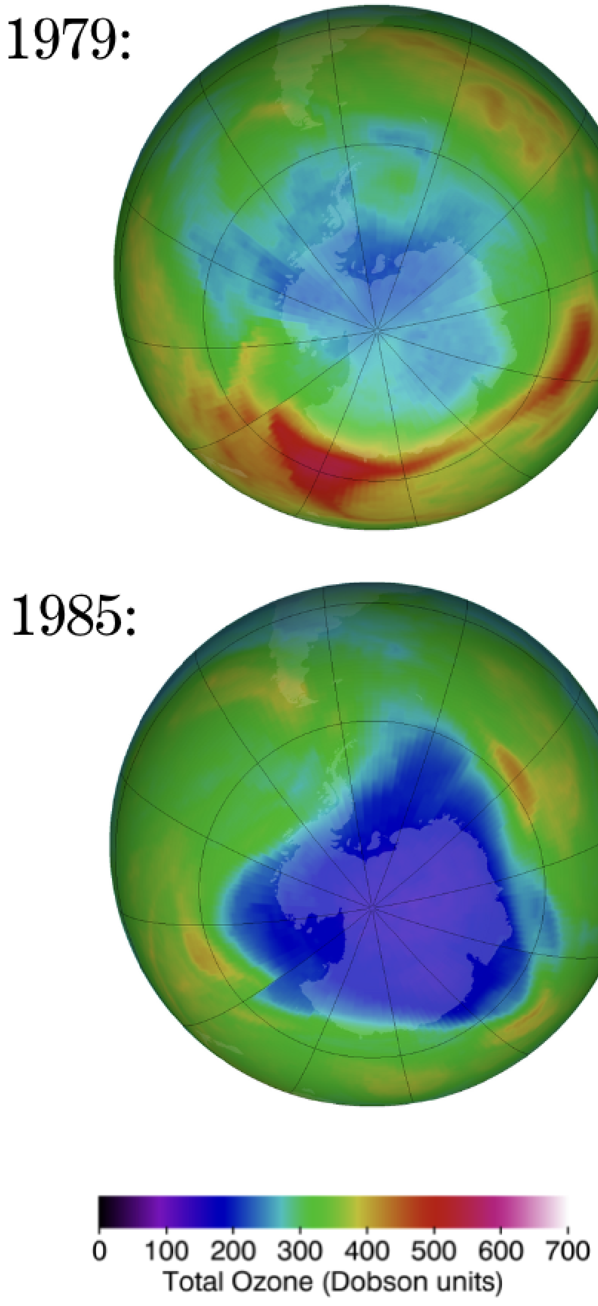


Figure 10: False-color view of total ozone over the Antarctic pole. The purple and blue colors are where there is the least ozone, and the yellows and reds are where there is more ozone. Images from (NASA Ozone Watch 2024)

B Appendix: Details of the Montreal Protocol

B.1 Countries affected by Article 5

One of the key elements of the Montreal Protocol is that countries were separated into "groups" which had different reduction schedules for their production and consumption of CFCs (and later this also applied to the Kigali Amendment). "Article 5" countries are developing nations with annual consumption of controlled substances under 0.3 kg per capita. These countries can delay compliance with control measures by ten years, as long as their consumption remains below this threshold. They can base compliance on their lower average consumption from 1995-1997 or 0.3 kg per capita. Additionally, Article 5 countries receive support through access to alternative substances and technology, along with financial aid and other assistance.

The designation of Article 5 countries can change over time based on reassessments of their consumption levels of controlled substances. Specifically, Article 5.1 states that a country whose annual consumption exceeds 0.3 kg per capita at any point within ten years of the Protocol's entry into force may lose its Article 5 status. These countries are also subject to periodic reviews and adjustments as outlined in Article 5.8.

The full list can be found here: (UNEP Ozone Secretariat 2024a)

The full text is the following:

> Any Party that is a developing country and whose annual calculated level of consumption of the controlled substances is less than 0.3 kilograms per capita on the date of the entry into force of the Protocol for it, or any time thereafter within ten years of the date of entry into force of the Protocol shall, in order to meet its basic domestic needs, be entitled to delay its compliance with the control measures set out in paragraphs 1 to 4 of Article 2 by ten years after that specified in those paragraphs. However, such Party shall not exceed an annual calculated level of consumption of 0.3 kilograms per capita. Any such Party shall be entitled to use either the average of its annual calculated level of consumption for the period 1995 to 1997 inclusive or a calculated level of consumption of 0.3 kilograms per capita, whichever is the lower, as the basis for its compliance with the control measures.

(Ozone Secretariat 2024)

B.2 Phasedown schedule: Kigali Amendment

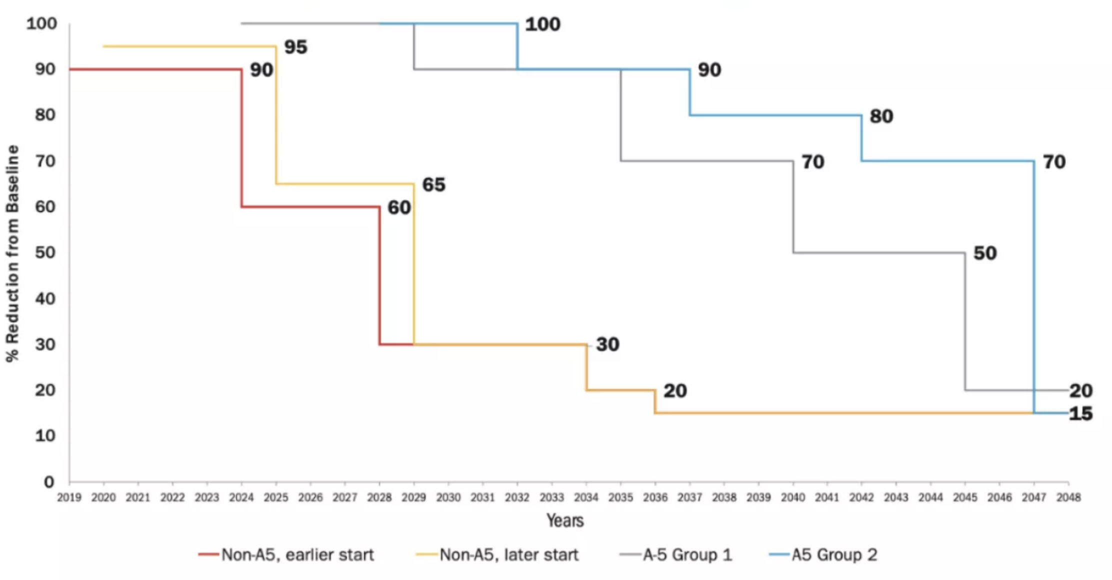


Figure 11: Objectives of the Kigali Amendment by development group (NRDC 2021)