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THE FEASIBILITY OF A GLOBAL NET ZERO FOR RACHP IN 2050: THE IMPACT OF MAIN PARAMETERS

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ABSTRACT

The 2015 Paris Climate Conference resulted in a decision to keep the global atmospheric temperature rise well below the pre-industrial one. It resulted in the publication of many climate-science reports, starting with the 1.5 °C IPCC Special Report, a definition of net zero emissions and possible pathways to achieve net zero by 2050, to control a further global temperature increase. It applies to all process emissions (a variety of gases) and all indirect "driver" emissions (from fuels, electricity production, etc.). RACHP, as an important player, would also need to comply with net zero targets. Banks and emissions -including energy efficiency- for developed and developing countries have been the subject of extensive spreadsheet studies to determine "zero" emissions. In this paper, the main factors for simplified calculations of the impact of RACHP-related emissions during 2020-2050 are determined, for developed and developing countries, and globally - including growth assumptions. Next, a scenario approach enables the performing of sensitivity analyses to determine to what extent net zero can be reached. Several parameters are examined quantitatively: (1) refrigeration capacities, i.e., inventories produced and banked, versus growth (assuming certain equipment refrigerant charge and leakage), (2) GWPs --while equipment refrigerant consumption in CO_2-eq. has to (at least) comply with Kigali measures--, (3) energy efficiency, and (4) electricity using certain kg CO_2/kWh assumptions. (1) and (2) determine HFC refrigerant emissions in CO_2-eq., (3) and (4) the electricity production-related CO_2 emissions. Both can be compared for various scenarios. Sets of results yield an overall view of the possibilities and challenges for achieving a global 2050 RACHP net zero.

Keywords: energy efficiency, energy mix, modelling RACHP, net zero, renewables,

1. INTRODUCTION AND CONTENTS SUMMARY

The paper starts with the Paris Agreement and subsequent IPCC reports, such as the Special Report on 1.5 °C and various IPCC Sixth Assessment reports. This then leads to the issue of net zero in general, also related to Nationally Determined Contributions NDCs). After having elaborated on currently relevant climate issues (from an international point of view, it explains the need for a good understanding of how RACHP needs to take courses for achieving the net zero 2050 target. For the whole of net zero, the decarbonization of the energy sector and the use of renewable energy are very important climate-related topics. Meeting the global electricity demand (including RACHP) with renewable energy to reach net zero is a real challenge. Moreover, the renewable electricity supply to the RACHP sector must be synchronized with the total amount required for all uses. The paper proceeds with net zero issues focusing on RACHP-related emissions and how total emissions could be globally brought to zero by 2050. Many qualitative considerations have been published, such as e.g., the "Keeping it Chill" report (UNEP, 2023b). The study described in that report focused on RACHP emissions via a complex multi-country, multi-sector model for deriving refrigerant emissions in certain years while using various parameters. Undoubtedly, this yields overall emission results that are clear, but challenging to interpret, also where it concerns any renewable energy component.

This paper is based on a sensitivity analysis of the impact of the most important parameters, using a "relatively simple" RACHP-based spreadsheet model. The input data used are explained and a time series (baseline) for 2000-2020 will be constructed. Certain scenarios are then selected for 2020-2050, based on several parameter assumptions. HFC emissions calculated for the 2020-2050 period are compared with emissions from electricity generation, where the fuel/renewable mix in the electricity is used as a parameter. The results from various scenarios should provide insight into whether and how a "2050 net zero" for RACHP would be achievable.

Section 2 deals with the Paris Agreement and IPCC reports, and section 3 with NDCs. Section 4 gives some results of the COP28 Global Stocktake. Relevant international developments and the current status of climate issues are presented in sections 5 and 6. The way RACHP has been dealt with at COP28, including the Cooling Pledge, is provided in section 7. Section 8 focuses on the main issue of the paper and outlines details of the model used, and how various parameters are being applied. Section 9 presents the results of a few sensitivity analyses. The paper ends with a list of conclusions in section 10.

2. THE PARIS AGREEMENT AND IPCC REPORTS

In 2015 (at COP21), the Paris Agreement concluded the following: *"the long-term temperature goal is to keep the rise in global average temperature to well below 2 °C above pre-industrial levels, and to pursue efforts to limit the increase to 1.5 °C, recognizing that this would substantially reduce the risks and impacts of climate change. This should be done by reducing emissions as soon as possible, to 'achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of the 21st century'*. The balance mentioned here after 2050 is defined as *'net zero'*. The Paris Agreement specifically decided on the submission of NDCs which should describe (**i**) plans for how to decarbonize -per country-, (**ii**) pathways for decarbonizing all relevant sectors, and (**iii**) how one could increase renewable energy capacities.

As a result of COP21, the IPCC (2018) assembled a Special Report on 1.5 °C, describing the "why" of 1.5 °C as well as pathways for mitigating climate change so that the average global temperature can be kept at a maximum of 1.5 °C higher than the pre-industrial (1850-1900) temperature average. This IPCC report states that **(1)** reductions in net emissions should be achieved through consistent mitigation measures, and that **(2)** future radiative forcing from cumulative emissions of CO_2 -and non-CO_2 greenhouse gases- determines whether one can limit global warming to 1.5 °C by 2100. Net global human-caused greenhouse gas emissions (Figure 1 below) would need to decrease by ≈45% from a 2010 level by 2030, reaching net zero around 2050.

The IPCC Sixth Assessment Report (AR6) is another result of COP21. The IPCC AR6 Working Group III report (IPCC, 2022) expands on the 1.5 °C IPCC Special Report. At its release: *"It's now or never if we want to limit global warming to 1.5 °C"* (Skea, 2022). It was stressed that limiting warming to around 1.5 °C requires global greenhouse gas emissions *to peak before 2025 at the latest*, and be reduced by 43% by 2030.

3. NATIONALLY DETERMINED CONTRIBUTIONS (NDCs)

The Paris Agreement decided that country emission reductions should be realised via the development of voluntary NDCs. As the UNFCCC (2021) states: *"Nationally determined contributions (NDCs) are at the heart of the Paris Agreement and the achievement of long-term goals. NDCs embody efforts by each country to reduce national emissions and to adapt to the impacts of climate change. [..]. Together, these climate actions determine whether the world achieves the long-term goals of the Paris Agreement and to reach global peaking of GHG emissions as soon as possible and to undertake rapid reductions thereafter in accordance with best available science [.....]. To enhance ambition over time [...], successive NDCs will represent progression compared to previous NDCs reflecting highest possible ambition"*.

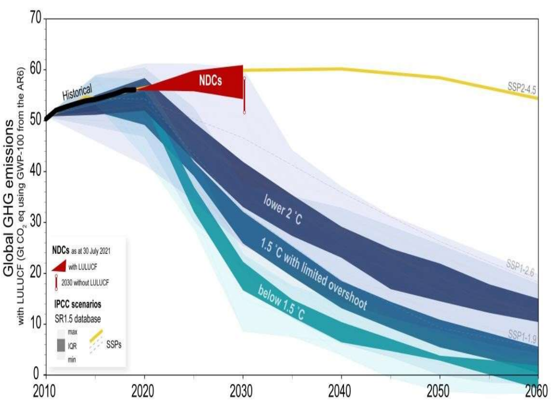

Fig. 1: Comparison of global emissions under scenarios assessed in the IPCC (2018) Special Report on 1.5°C with total global emissions according to the integrated NDCs (UNFCCC, 2021).

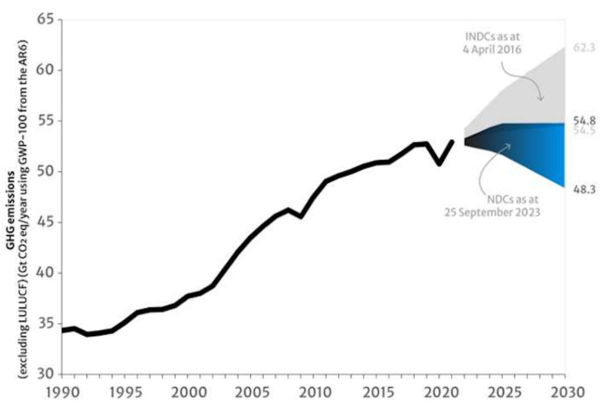

Fig. 2. Comparison of global emissions during 1990-2021, and expected emissions following 2023 NDCs up to 2030 (UNFCCC, 2023). Emissions are expected to remain the same in 2030, at a maximum of 10% lower.

Both Annex I and non-Annex I countries have many common elements in their NDCs towards emission reductions. They must depart from economic growth, impacting many parameters to be considered (Kuijpers et al. (2022)). As such, RACHP net zero strategies can therefore not be derived from countries' NDCs.

Moving to a comparison of 2050 net-zero targets and the "NDC reality" (i.e., Figures 1 and 2 above), the UNFCCC (2021) mentions: "A credible, obvious observation is that the NDCs (which include all industry, transport, building, cooling-heating sectors, etc.) need to present a total picture of how countries are planning ways to net-zero, if possible, by 2050, which is often lacking"; also elaborated upon in (WRI, 2022).

As of 2020, many governments made long-term NDC-based "vision plans". Most of these NDCs have very few consequences in the short term, even when short-term measures are proposed via internal government measures (i.e., they are constantly subject to changes). According to Chatham House (2022), not enough is being done to transform society into a net zero one: "Current global climate action is starkly insufficient". About 35% (70) of a total of 197 countries had NDCs with a *well-planned net-zero target* in September 2022.

The UNFCCC (2023) issued a new NDC Synthesis Report in September 2023. It synthesises information from the 168 latest available NDCs. Twenty parties communicated new or updated NDCs since September 2022, a relatively small increase. Total global GHG emissions taking into account implementation of the latest NDCs are estimated to be around 1.6 Gt CO2 eq. in 2030. This is > 8% than in 2010, < 2% than in 2019, and < 3.1% than the estimates for 2025, indicating the possibility of global emissions peaking before 2030. Figure 2 shows a maximum expectation of a 10% decrease in global emissions by 2030 (*note:* current NDCs often do not include emissions of all greenhouse gases). This confirms the 2022 conclusion by Chatham House that global climate action is starkly insufficient. WRI (2024) proposes a five-point plan for new NDCs.

Globally, the percentage of countries planning a 2050 net zero target is still perceived as small (<50%) --their emissions percentage in the total is likely even smaller since many large emitters do not have a good 2050 target--. It shows a "major emissions gap" between emissions following net zero pathways and the reality. This also applies to "businesses", where hundreds of businesses drop net zero commitments due to Scope 3 challenges and uncertainties about the future (edie, 2024). So-called 'greenhushing' is on the rise as companies go silent on climate pledges, definitely in certain regions. Since they are facing backlash from both the left and right, companies are backing away from climate initiatives - at least publicly (Today's Climate, 2024).

Considering specific RACHP actions or pathways, these are difficult to interpret within the whole framework as currently created: (1) there is no good number for the percentage of RACHP emissions in the total, (2) developing countries, supported by the Montreal Protocol Implementing Agencies, develop "National Cooling Plans" (NCPs), that shall be part of their NDCs, while developed countries do not follow this NCP way. It is actually not (yet) clear how RACHP (emissions) can be addressed globally - to reach a net zero in 2050.

First impressions of net zero RACHP pathways were presented by Kuijpers et al. (2021) and by Hesse et al. (2022) in a net zero overview for the German Refrigeration Society (DKV).

4. COP28: THE GLOBAL STOCKTAKE

In December 2023, COP28 started with the bang of a landmark agreement on loss and damage and also agreed on several pre-prepared alliances, coalitions, pledges, and declarations --all in separate settings-- during the first days of the COP (ENB, 2023). Even with the initial high points, negotiations throughout the two-week conference were difficult, especially on the main outcomes planned for COP28: (1) the first Global Stocktake (GST) under the Paris Agreement, (2) the Global Goal on Adaptation (GGA), and (3) mitigation work.

Parties adopted a decision related to the GST that recognizes (again) the need for deep, rapid, and sustained reductions in GHG emissions in line with 1.5 °C pathways, i.e., parties were encouraged to ensure that their next NDCs (in 2025) have *ambitious, economy-wide emission reduction targets, covering all GHGs, sectors, and categories,* consistent with the 1.5 °C limit (*note:* it implies a substantial change to the 2023 updated and new NDCs and the emissions values given for 2030). Chatham House (2023): "Hailed as groundbreaking by the host, the UAE, and criticised as insufficient by climate-vulnerable groups (e.g., the Alliance of Small Island States (AOSIS)), the agreement is, in fact, both. The context for this duality is the slow speed of climate action to date. COP28 marked the first conference in which any explicit reference to moving away from 'fossil fuels' made it into the final decision text. This long-overdue achievement occurred as the understanding of climate change and discussions on climate action have become mainstream and climate impacts grow more severe."

The Financial Times heading was: *"COP28 is better than feared, but less than needed".*

5. PREVIOUS INTERNATIONAL DEVELOPMENTS

Substantial environmental developments started 60 years ago, with the book "Silent Spring" by Rachel Carson (1962). After that, "The Limits to Growth" for the Club of Rome (1972) was a bestseller (updated in 2022). The major elements addressed here were industrialisation, population growth, food starvation, the use of the Earth's resources, and various types of pollution, including climate; however, at that stage, the climate issue was seen as much different from now. It took years before concrete actions followed (see (Kuijpers et al., 2023)). The Vienna Convention on the Ozone Layer was adopted in 1985, *its Montreal Protocol in 1987,* and the Intergovernmental Panel on Climate Change (IPCC) was established in 1988. On climate, after years of standstill (2000-2012) and much preparatory work, efforts resulted in an agreement at the Paris COP21, including *voluntary*, national (climate-related) contributions (NDCs) (see section 2). In 2016, the Montreal Protocol adopted the first binding climate framework for HFCs, the Kigali Amendment, a major achievement. Simultaneously with the 2022 publication of the IPCC AR6 reports, the global supply of fossil fuels was seriously restricted, fuel prices increased and various scenarios were worked out to guarantee enough fossil fuel supplies for (separate) developed countries. By then, it led to multiple developments and negotiations in a broad framework of what this would mean for net zero. The current climate issues status is given below.

6. CURRENT STATUS OF CLIMATE ISSUES

The year 2023 has been measured as the hottest year on record, with unexpectedly high global temperatures for the atmosphere and the ocean. The high ocean temperatures throughout 2023 led to the preliminary conclusion that one may not fully understand climate and warming effects, where warming might go more rapidly than expected, and which type of tipping points would be reached at short notice. This temperature rise "was really much quicker than we all anticipated" (IPCC chair Skea in the Financial Times (2024)). Relevant information on 2023 temperatures is given in (WMO, 2024) and (Nature, 2024). April 2024 showed that the annual global 1.5 °C temperature increase has now been exceeded since February 2023 (Copernicus, 2024), The urgency of ways to "really" get to net zero in 2050 should therefore be once more underlined.

The UNEP 2023 Annual Report (2024) stated: "Last year was one of broken records and broken promises. We saw new highs of greenhouse gas emissions, temperature records tumbling and climate impacts arriving stronger and faster. The finance to help vulnerable communities adapt to climate change isn't being delivered. At the same time, most of the Sustainable Development Goals (SDGs) are off track at the halfway point of the 2030 Agenda for Sustainable Development. [….] it is clear that slow action on the triple planetary crisis of climate change, nature, and biodiversity loss, and pollution and waste is a major driving force". The report also referred to the UNEP (2023) Emissions Gap report quoting UNSG Guterres: "The [UNEP] report shows that the emissions gap is more like an emissions canyon. A canyon littered with broken promises, broken lives, and broken records." Statements say that the world does not seem able to follow a balanced regime. While ways to achieve net zero emissions for a global society within planetary boundaries are considered urgent by many, the 1.5 °C target is more and more "put aside". Renewables are a major issue here, where their past, current, and future developments are given in (REN21, 2024). Currently, various (additional) major technologies are pushed to solve the climate crisis: **(1)** nuclear energy expansion – presently considered to be a sustainable, clean way forward, **(2)** measures to absorb CO_2 via Carbon Capture and Storage (CCS), and **(3)** atmospheric and solar geoengineering technologies (e.g., stratospheric aerosol injection, with unknown side effects). At present, many countries seem to go for CCS, while even allowing the use of fossil energy to continue. Creating net zero NDCs in this way *remains highly questionable* (New Scientist, 2024). *It seems as if timescale issues have been forgotten:* the time to study and implement all major new technologies will take at least a decade, while reductions need to happen as soon as possible "to bend the curve". It underlines the need for many small-scale measures and behaviour changes for demand reductions during 2024-2040. The currently growing influences of right-wing parties in many countries that -based on climate denial- result in delaying or even cancelling many national and supra-national climate measures need to be taken into stern account as well - while some people go for legal procedures to get it climate-right (Chatham House, 2024a).

In summary, one seems to be building a "climate emissions-future" (and related reductions) on not well-established, proven technologies while going forward following a business-as-usual scenario for "expansion". This also happens without taking into account a natural balance between mankind, nature (biodiversity), and technology. IISD (2024) mentions a report to the Human Rights Council that points to "inadequacies of voluntary normative frameworks for ensuring that businesses respect human rights and clarifies State obligations to protect the right […] to a clean, healthy and sustainable environment from harms caused by businesses". States are recommended to support *the prioritization of benefits, not profits*. It again points to the fact that the world is not yet prepared for a major environmentally balanced regime. UNFCCC Executive Secretary Simon Stiell, in his ***"Only two years left to save the planet"*** interview, explained all issues that need to be addressed, including finance in particular (Chatham House, 2024).

All this makes the "emissions future" uncertain, *in comparison to the 43% emission reduction propagated by the IPCC 1.5 °C and AR6 reports for 2030.* However, considering it as the best way forward, given many boundaries, the model presented below has to follow the IPCC 2030-50 pathways principle.

7. THE PLEDGES AT COP28

This section deals with two pledges at COP28 and their relationship to RACHP-related emissions. During the first days of COP28, one concluded on texts of two important pledges. The ***"Global Renewables and Energy Efficiency Pledge*"** from the EU (signed by 118 countries) aims at tripling renewable energy capacity and doubling energy efficiency measures annually until 2030. It was adopted because the EU supports it with funding; IRENA is tasked to monitor the progress (IRENA, 2024). The EU pledge concerns all sectors, of which the whole of RACHP is only a small part, and commits to **(1)** work together to collectively double the global average of energy efficiency improvements from ≈2% to ≈4% per year until 2030 (i.e., 30% instead of 15% until 2030), to **(2)** put energy efficiency as the "first fuel" at the core of policymaking, and to **(3)** increase renewable energy capacity and make major investment decisions. The ***"Cooling Pledge"*** by the Cool Coalition (UNEP, 2023a), signed by 66 countries, commits to support robust action through the Protocol Fund for early action to reduce HFC consumption and to promote improved energy efficiency for the HCFC phase-out and HFC phase-down. It aims at raising ambition and international cooperation via collective global targets ***to reduce cooling-related emissions by 68% from today*** *(base 2022) in 2050,* significantly increase sustainable cooling access by 2030, and increase the global ***average efficiency of new air conditioners by 50%***. This 2022 baseline also applies to the 50% efficiency increase of AC units by 2030, however, one refers to the efficiency of *the **global bank** of air conditioners* in 2022, the determination of which is challenging, i.e., it is not the efficiency of products *sold* in 2022. So, the 50% increase by 2030 is likely complicated to determine. While the emission target draws on modelling from the UNEP (2023b) "Keeping It Chill" report, the "precise" Pledge data had no concrete (global) background and they lacked ways to check for achieving the targets mentioned.

Particularly the aspects of emission reductions (and this combined with energy efficiency aspects) in the UNEP report have led to the model study done for this paper, that is, to investigate net zero possibilities for RACHP (combined with electricity-based emissions) via several scenarios, using a simplified model. The paper will single out RACHP as the important sector that can give an exemplary approach to reaching net zero.

8. APPLYING A "SIMPLIFIED" GLOBAL EMISSIONS MODEL

This "simplified" (global) model is set up as follows:

(1) Developed and developing countries are split for the sectors of refrigeration, AC, and heat pumps while the developing countries are (additionally) split into Groups 1 and 2 following Kigali (this applies to HFCs). For 2020-2050, it combines "results" from all countries and the three sectors for a global result.

(2) Starting values are the annual energy consumption values for developed and developing countries during 2000-2019, and the assumption from (IIR, 2019) that R/AC uses 20% of total electricity production. Global energy consumption values are taken from (IEA, 2023) and (OECD, 2022), and 2021 country consumption values are from Wikipedia (2023), so that the complete Article 5 developing country group can be estimated. The share of developing countries' consumption in the total is ≈60% (for the year 2021).

(3) The lifetime of all RACHP equipment is assumed to be 20 years for 2000-2020 and 2021-2050.

(4) For the period 2000-2020, the annual energy consumption is combined with certain assumptions made for the energy efficiency of equipment. This may seem easy, but one has to assume values for the RACHP subsectors in 2020 based on new HFC equipment and energy efficiency increases during 2000-2020 to determine the "energy efficiency of the 2020 bank", resulting in the calculation of available refrigeration capacities (from 2000) in 2020 (being the baseline used for everything to be calculated after 2020).

(5) The model uses an average charge for all equipment in developed and developing countries of 0.4 kg per kW (this could be changed, but, in the first instance, it is used as a constant for the entire period 2000-2020 (and up to 2050) since the variation of other parameters (such as the GWP) is thought to be more important.

For the bank replacement (i.e., how the bank is gradually replenished with new amounts), a stepwise change of parameters (e.g., GWP, energy efficiency) is calculated as an impact on the total annual bank (see Annex 1) by the use of the formula (*note:* after one equipment lifetime, the bank will have adopted new values):

$f = g\,(1+g)^{L-1} / [(1+g)^{L} - 1]$, *with f=fraction of the bank, g= annual growth, L = lifetime of the equipment*

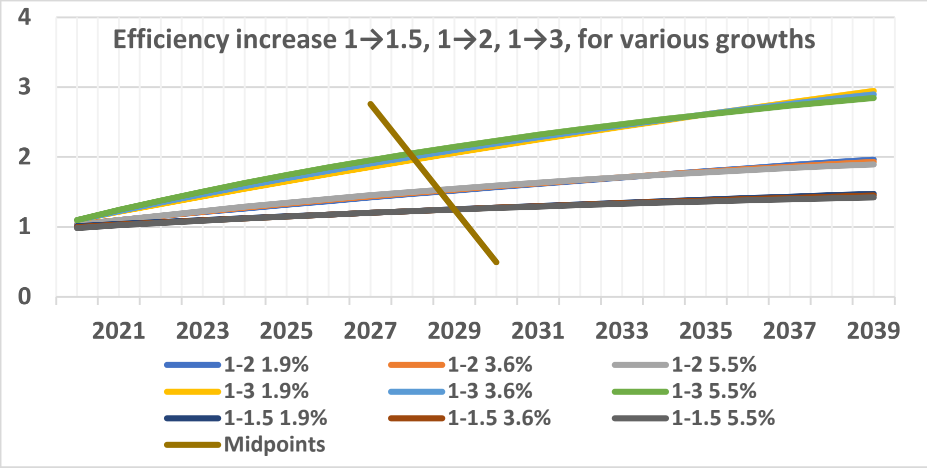

Fig. 3: Relative energy efficiency increases of the annual equipment bank, once an energy efficiency increase is introduced in a certain year (2019), over 20 years (i.e., the equipment lifetime) for three growth percentages. The line depicting midpoints for the various curves shows that the efficiency more or less follows a linear approach.

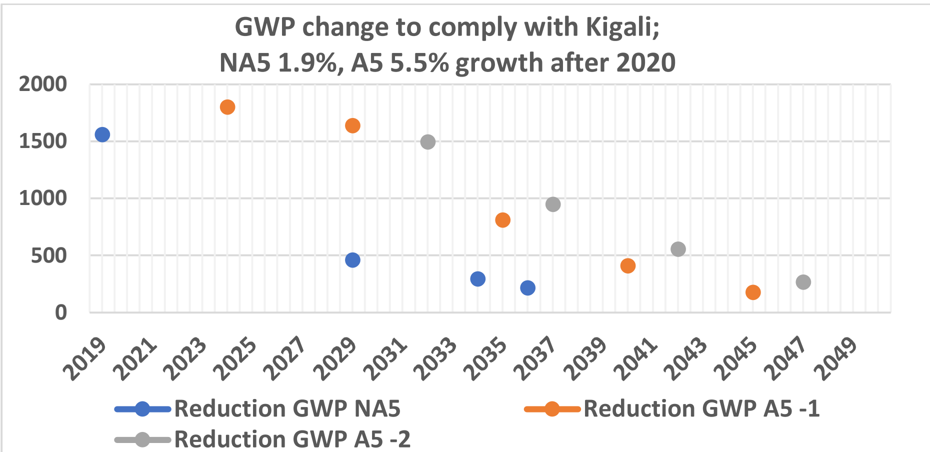

Fig. 4: The GWP decrease necessary (GWP as a starting point=1800) to comply with Kigali targets, using certain growth percentages for annual amounts produced (Article 5 countries have been split into the two groups following Kigali) (Note: the different timescale compared to Figure 3) (Note: Kigali does not go to zero CO_2 eq. consumption).

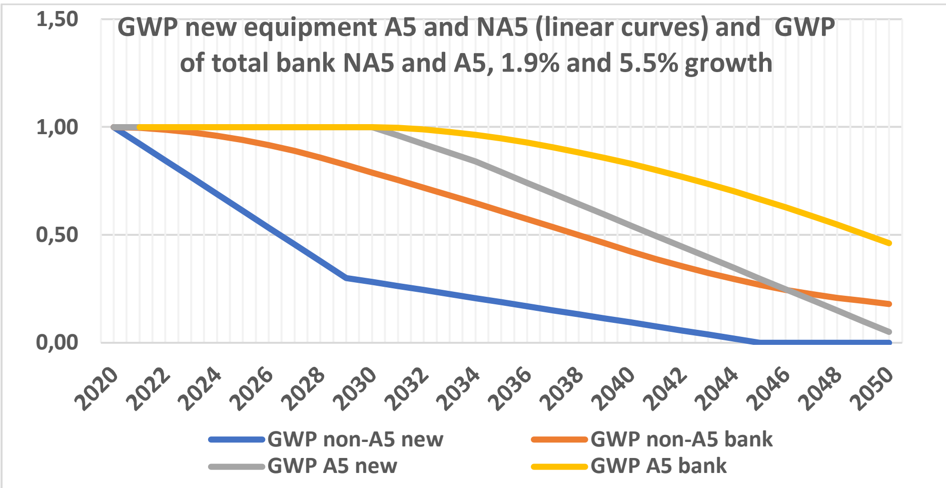

Fig. 5: The GWP decrease necessary (in a relative sense) to comply with Kigali consumption, using certain growth percentages (linear curves), and the average GWP of annual bank amounts as a result (Note: GWPs are assumed constant until the year of reductions, i.e., for Article 5 countries after first reductions prescribed for 2029/2033).

The following comments apply to the modelling as done for the 2020-2050 period.

Introducing changes in energy efficiency will *gradually* impact the bank efficiency but will not at all influence the capacities (i.e., the equipment bank or the inventories in equipment). The important issue is that energy efficiency changes will ***only*** yield changes in annual energy consumption values (from the bank) which are important for determining the indirect emissions from electricity production. To simplify, the trend in the bank's energy efficiency after a step change has been calculated per year for certain growth percentages (see Figure 3, for various changes introduced as of 2020), which is then used in the model.

GWP changes will *gradually* impact the total capacities (i.e., the equipment bank), dependent on the equipment lifetime, and the assumed growth percentage of capacities. GWP values are selected separately for developed and developing countries and the three RACHP subsectors during 2020-2050 (while assumed to remain constant during 2000-2020). Even when certain regions may or will have larger reductions than prescribed by Kigali, the Kigali decrease is *used as the base case for the 2020-2050 period* for compliance, i.e., a BAU (Kigali) increase in consumption (and the resulting banks) after 2020 (given in Figure 4). Similar to energy efficiency, the trend in GWP values resulting from the bank has been calculated per year for certain growth percentages (Figure 5), in the same way as for the energy efficiency bank values, and is used in the calculations.

Hence, the main parameters for sensitivity analyses with the model as developed are:
(1) growth percentages for developed and developing countries;
(2) a faster decrease in GWP values than needed if one would just comply with Kigali during 2020-2050, resulting in a gradually lower GWP of the total bank and lower bank emissions (in CO_2-eq.);
(3) energy efficiency increases over a certain period;
(4) the amounts of CO_2 produced per kWh of electricity generated.
Where (1) and (2) have an impact on refrigerant emissions, (3) and (4) influence energy production-related emissions. These four parameters are adequate to derive direct, indirect, and total emissions (2020-2050) for developed and developing countries, and globally - and to combine all information in relevant figures.

9. THE SENSITIVITY ANALYSES ONLY

Several cases have been investigated as presented in Table 1.

CASE	Growth NA5	Growth A5	Efficiency NA5	Efficiency A5	GWP and electricity emissions (kg CO_2/kWh) NA5	GWP and electricity emissions (ibid.) A5
Base case	**1.9% (1)**	**5.5% (1)**	**Sector dep (1)**	**Sector dep (1)**	**0.35 (1)**	**0.6 (1)**
CASE A	1	1	1 as of 2020	1 as of 2020	1	1
CASE B	1	1	2 as of 2020	2 as of 2030	1	1
CASE C	1	1	2 as of 2020	2 as of 2030	0.7- 2030 / 0.1 - 2050	1
CASE D	1	1	2 as of 2020	2 as of 2030	0.7- 2030 / 0.1 - 2050	0.8-2040
CASE E	1	1	2 as of 2020	2 as of 2030	0.7- 2040 / 0.1 - 2050	0.6-2040
CASE F	1	1	E+ 3 as of 2030	E+3 as of 2040	1	1
CASE G	1	1	E+ 3 as of 2030	E+3 as of 2040	0.7- 2040 / 0.1 - 2050	0.6-2040
CASE H	1	0.67	2 as of 2020	2 as of 2030	0.4	0.4-2040
CASE I	1	0.67	3 as of 2030	3 as of 2040	0.4	0.4-2040
CASE K	1	1	E+ 3 as of 2030	E+3 as of 2040	GWP 0.5 (as of 2030) elct. 1	GWP 0.5 (as of 2030) elct. 1
CASE L	1	0.67	E+ 3 as of 2030	E+3 as of 2040	GWP 0 (sp 2030) elct. 1-2020 / 0.1-2050	GWP 0.2 (sp 2030) elct. 1-2020 / 0.4-2050

Table 1: The base case is defined where it concerns growth, efficiency, and electricity emissions (kg CO_2/kWh) (which is also Case A, with all values set to 1 for the base case). Cases A to L present several possibilities to vary the efficiency, the emissions from electricity generation, the growth percentage, and the decrease of the GWP (for cases K-L: a lower GWP is assumed to start in 2030 for developed and in 2040 for developing countries).
(Note once more: ALL values for cases A to L in the table are *relative* to the absolute base case values)

The above cases are just a selection assumed to give adequate insight. Two base case figures 6 and 7 are shown below because of their relevant information. Rather than going to values from the Cooling Pledge (e.g., for AC), this gives a good picture of the anticipated BAU's direct and indirect emissions during 2020-2050.

The set of figures shows the major trends and points at which parameters need further investigation:

1. Refrigerant emissions from developed countries are small compared to the ones from developing countries for the base case (applying the necessary Kigali reductions via GWPs and also for all other assumptions).
2. Even for a 5.5% annual growth of developing countries' capacities, their refrigerant emissions (HFCs) start to decrease gradually after 2040, due to the Kigali-mandated reductions (via decreases in the GWPs of refrigerants). The developing countries' emission increase in 2050 compared to 2022 is slightly higher than 80% (whereas the global refrigerant emissions increase from 2022 to 2050 is calculated to be ≈50%).
3. Emissions from electricity production for RACHP in developed countries are (much) smaller than the refrigerant emissions from RACHP equipment in developing countries when using base case assumptions.
4. To achieve net zero by 2050 globally, the two major elements that play a role are **(a)** decreasing developing country refrigerant emissions, and **(b)** decreasing the emissions from developing country electricity production ***where the latter is dominant***.

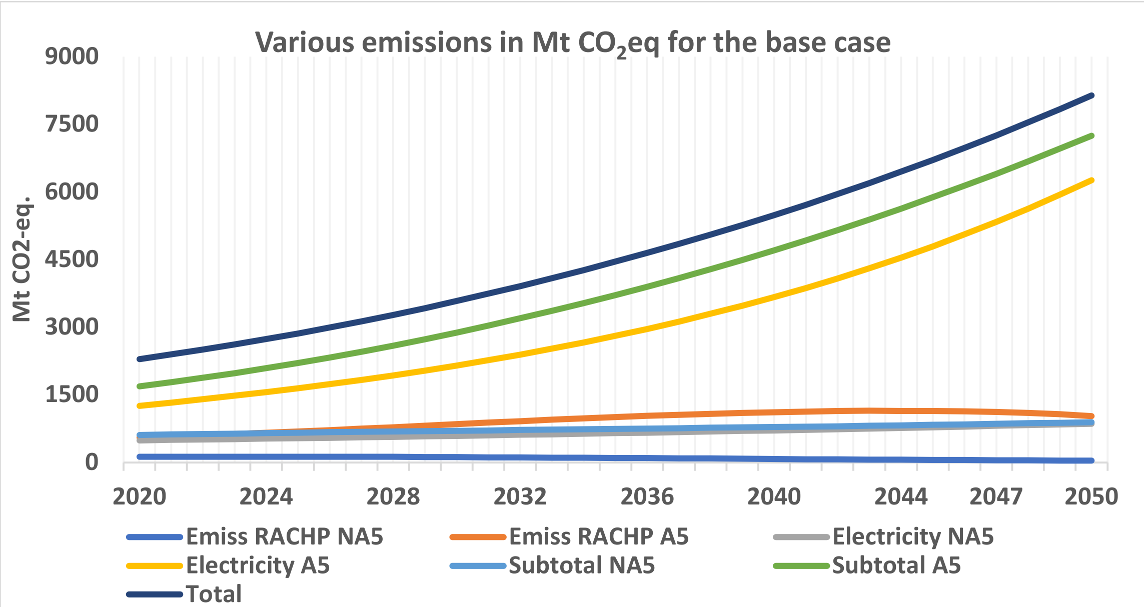

Fig. 6. Base case emissions from RACHP equipment and electricity production, for developed and developing countries, plus global emissions (period 2020-2050). Electricity-generation-related emissions from non-Article 5 countries are small, even in the case of a large heat pump capacity. Article 5 electricity-related emissions are predominant; both energy efficiency and renewable energy increases are important for reducing these emissions.

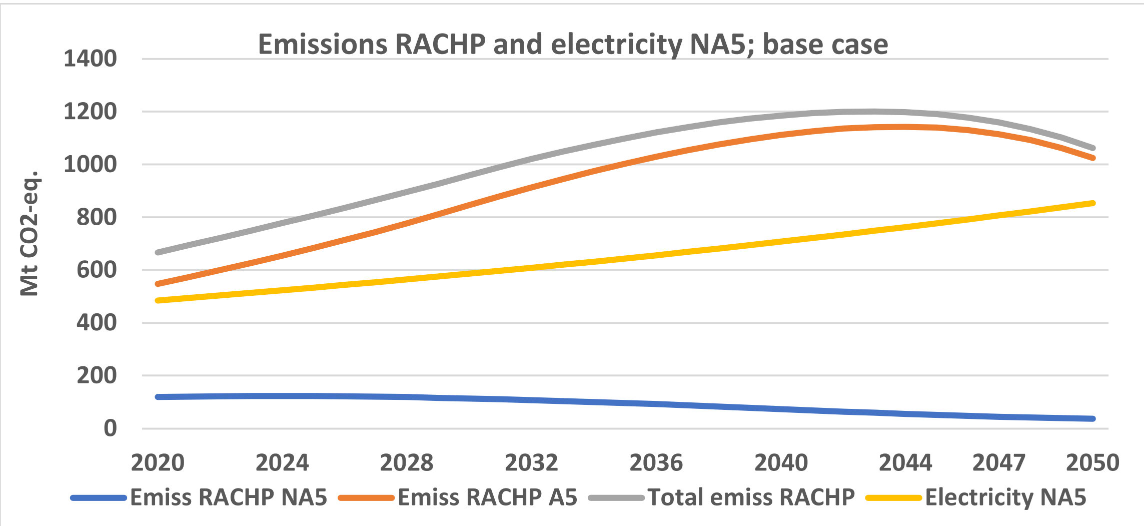

Fig. 7. Details from Fig. 6: Emissions from refrigerant equipment for developed, and developing countries and globally, as well as the emissions in developed countries from electricity production over the 2020-2050 period.

Given all the above, several parameters have been examined on a one-by-one basis, given in Table 1. However, all the results calculated cannot be presented in this paper. For this reason, one more figure is given below, which shows the results from the most drastic change in all relevant emission parameters (Case L):

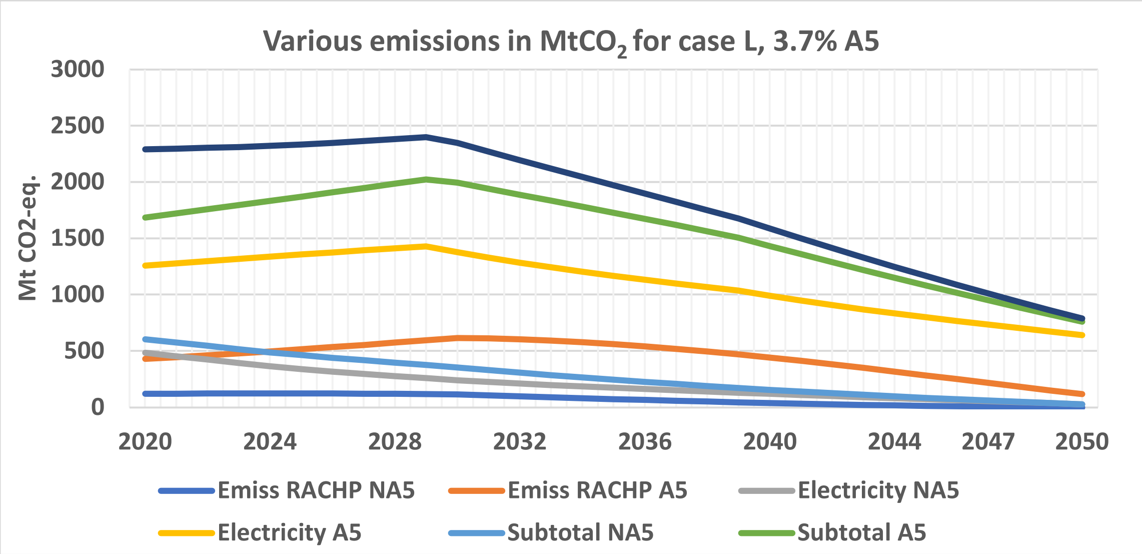

Fig. 8. Emissions from RACHP equipment and electricity production for Case L for developed and developing countries, and globally, all for 2020-2050 (Note: there is a *difference in scale of a factor of 3* with Figure 6).

a. For developing countries, zero refrigerant emissions in 2050 cannot be realised without applying low or negligible GWP solutions early on (around 2035), which is faster than any Kigali reductions would require.

b. For developing countries, Figure 8 shows that a significant reduction can be achieved if refrigerants with a GWP of 0.2 relative to the base case (i.e., an average GWP of ≈400) start to be applied as of 2030 (this will then lead to a complete change of "the GWP of the developing countries bank" in 2050).

c. Figure 8 shows the developing countries' refrigerant emissions approaching low values in 2050, even with a 5.5% growth in capacity (this after a maximum in emissions of about 730 Mt CO_2 eq. in 2033). The refrigerant emissions from developed countries are assumed to be much smaller (maximum of about 120 Mt CO_2 eq. in 2023-24), due to zero GWP refrigerant equipment applications assumed to start in 2030.

d. For Case L, developing countries' refrigerant emissions are 80-90% of total global refrigerant emissions during 2020-2034, and 90-100% of the ones during 2035-2050 (*Note:* the emissions scale in Figure 8 is 33% of the one in Figure 6 (base case)). The 2050 refrigerant emissions are ≈20% of the ones in 2020. For a 5.5% growth, the 2050 emissions happen to be ≈30% of 2020 (as in "Keeping it Chill" (UNEP, 2023b)).

e. The emissions from electricity generation are, in fact, a separate issue. In developed countries, they can be pushed to very low values (even with a high heat pump percentage) as for case L, by assuming large percentages of renewables (from 40% in 2030 to over 80% in 2050). The issue is different for developing countries, nevertheless, case L ***assumes*** that a "40% renewable" level could be reached here by 2050.

f. Figure 8 shows that the electricity emissions from developing countries are dominant, even if compared with the total global emissions up to 2050. It will be clear that large (during 2030-40) to very large percentages of renewables (during 2040-50) can change this picture. Which percentage of renewables could be assumed for developing countries during the 2040 decade is not yet clear (here 40% is used).

g. A net zero for refrigerant emissions may be achieved by the decrease of global refrigerant emissions to a large degree, once adequate reduction measures are applied. However, a total net zero will be very much dependent on the emissions from electricity generation. If the latter cannot be brought to zero in 2050, one *might even discuss* whether (global) refrigerant emissions need to get to a complete zero" in 2050.

10. CONCLUSIONS

- The Paris Agreement from 2015, including the resulting NDC approach, seems to be the best voluntary method to introduce net zero plans by 2050. Before that NDCs will be good enough to present a complete trajectory for net zero by 2050, many more efforts will be needed. This will not be shown before the 2025 COP30 meeting in Brazil. Many NDCs do not yet have good RACHP emissions strategies (in NCAPs).
- The lack of good emission strategies has been shown by past NDCs, and by COP28 discussions in Dubai. On RACHP, the Cooling Pledge in Dubai was one more effort to get the RACHP sector on track to 2050. However, even when it is a global pledge to go forward, it is likely insufficient to bring the RACHP sector to a ***total*** net zero – this should also include all the emissions from electricity production it will generate.

- The implementation of sustainable net zero plans is going forward; however, it also encounters delays. This happens while international climate mitigation developments are currently hampering; on the other hand, climate developments (related to atmospheric and ocean temperatures) seem to have a different, shorter timescale than expected, emphasising the urgency to achieve net zero emissions by 2050.
- The study reported here is related to the fact that the emission picture from the UNEP (2023b) "Keeping it Chill" report (and the actions described in the Cooling Pledge) may well need further information to give a transparent idea of what would need to happen to go to a complete net zero by RACHP, globally.
- For this reason, a simplified emissions spreadsheet model was developed for sensitivity analyses (two issues were studied in particular): (1) the electricity needs for RACHP, and (2) the decreasing HCFC use before 2020, both in developing countries). Furthermore, the current study could not address an "infinite" number of changes and therefore focused on four relevant parameters.
- Base case ***refrigerant*** emissions from developed countries are small compared to the ones from developing countries (applying necessary Kigali reductions via the GWP). The global base case refrigerant emissions increase is calculated to be about 200% by 2050, vs. 2020. There is an emissions decrease of ≈70% in developed countries, but a dominant increase in developing countries (yielding large increases by 2050).
- It implies that major efforts need to be made to obtain a global refrigerant emissions reduction, as, for instance, the 68% reduction mentioned in the UNEP (2023b) Keeping it Chill report. This cannot be achieved via efficiency increases (assuming capacities will grow). It has to be done via a decrease in the GWP and equipment parameters. It can, of course, also be realised via demand reductions (i.e., lower growth). This study focuses on GWP which yields a charge and leakage decrease in parallel (in Mt CO_2-eq.) but no extra reductions for charge and leakage are assumed here (so, for additional studies).
- Developed country emissions from electricity production are much smaller than refrigerant emissions from developing countries (2020-2050). The emissions that really count are the ones from electricity production in developing countries, which will therefore be the major factor in achieving a net zero globally by 2050.
- This study also investigates how emissions would change in case of very large efficiency increases, and GWP reductions to 10-20% of the 2020 ones as of 2030 (having a full effect on the 2050 refrigerant bank), and increases to renewable energy of ≈90% in developed, and ≈65% in developing countries (in 2050).
- When applying such changes in parameters, a lot can be achieved compared **to 2020**, i.e., reductions (1) to very low values of total developed country emissions, (2) to 55% of developing country refrigerant emissions, (3) to very low electricity-related emissions in the developed, and (4) to 20-30% reductions in developing countries. The reduction in total global emissions from RACHP in 2050 would be around 45%.
- For RACHP, if net zero is to be achieved in 2050, additional measures for equipment emission reductions in CO_2-eq are necessary. The major issue will be to reduce electricity-generated emissions in developing countries during 2030-50. ***Net zero cannot happen without a zero from electricity production emissions.***
- This has been a preliminary investigation but it is thought to have adequately demonstrated the impacts of all important RACHP and electricity generation parameters.

11. ACRONYMS

Annex I	Developed Countries (UNFCCC)
Non-Annex I	Developing Countries (UNFCCC)
AR6	6th IPCC Assessment Report
BAU	Business as Usual Scenario
COP	Conference of the Parties
COP	Coefficient of Performance
GWP	Global Warming Potential
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
NCAP	National Cooling Action Plan
NDC	Nationally Determined Contribution
OECD	Organization for Economic Cooperation and Development
R/AC	Refrigeration and Air Conditioning
RACHP	Refrigeration, Air Conditioning, and Heat pumps
UNFCCC	United Nations Framework Convention on Climate Change
UNSG	United Nations Secretary-General

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ANNEX 1

DERIVATION OF THE REPLACEMENT RATE TO MAINTAIN A STEADY GROWTH

This annex will derive the fraction of new capacity needed each year in a simple market model having systems with constant annual growth and a fixed lifetime. The market definition uses the following variables:

- B(n) is the bank with a certain capacity in year n
- L is the lifetime of systems (in years)
- g is the annual growth (e.g., g = 0.02 means 2% growth per year), so after x years in the n^{th} year the size of the bank is: $B(n) = (1 + g)^{X} B(n-x)$
- N(n) is the new capacity installed in year n. This covers the replacement of systems that have reached their end of life, as well as the addition of new systems to maintain the preset growth.
- f is the fraction of new capacity installed in a year and is assumed to be constant over the years: $f = N(n) / B(n)$

The new capacity installed in year n can also be written as the bank that has reached the end of life plus the growth in the bank:

$$N(n) = N(n-L) + g\,B(n-1) \tag{1}$$

Inserting the definition of f:

$$f\,B(n) = f\,B(n-L) + g\,B(n-1) \tag{2}$$

Rewrite the equation in terms of B(n):

$$f\,B(n) = f\,B(n) / (1 + g)^{L} + g\,B(n) / (1 + g) \tag{3}$$

Multiplying with $(1 + g)^{L} / B(n)$ on both sides:

$$f\,(1 + g)^{L} = f + g\,(1 + g)^{L-1} \tag{4}$$

f can now be isolated, yielding the final result:

$$f = g\,(1 + g)^{L-1} / [(1 + g)^{L} - 1] \tag{5}$$