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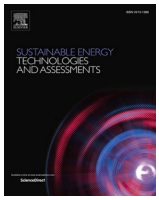

Metrics for the emissions of F-gas refrigerants

Nicole D. Miranda [a,c,*], P. Giovani Palafox-Alcantar [a,b], Radhika Khosla [a,b], Malcolm D. McCulloch [a,c]

[a] Future of Cooling Programme, Oxford Martin School, University of Oxford, Oxford, United Kingdom
[b] Smith School of Enterprise and the Environment, School of Geography and the Environment, University of Oxford, Oxford, United Kingdom
[c] Energy and Power Group, Department of Engineering Sciences, University of Oxford, Oxford, United Kingdom

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ABSTRACT

This paper examines the metrics used to account for the contribution to global warming from fluorinated gases (f-gases) mainly used as refrigerants for cooling. F-gases are key to climate mitigation discussion as they a) are critical to delivering the surging demand for air conditioners which is expected to triple by 2050, b) have strong Global Warming Potential (GWP) as high as 12,000 $kgCO_2$-eq (for e.g., HFC-23) and c) are targeted by international policy agreements such as the Montreal Protocol and Kigali Amendment. F-gases exacerbate atmospheric warming when leaked from cooling equipment, or during other phases of their life cycle. Thus far, the way these gases impact global warming is mostly reported based on their CO_2-equivalent emissions with a time horizon of 100 years. However, the problem is that f-gases have significantly different lifespans and the GWP_{100} does not account for these variations. The debate on metrics to account for warming of other short-lived climate pollutants (SLCP), such as methane is already ongoing. Here, we provide the first step to open such debate for short-lived f-gases. We address this, first, with a critical review of the available metrics for carbon foot-printing of f-gases and present a gap analysis between the existing carbon foot printing metrics and the need to better understand warming from f-gases. Second, we use an atmospheric model to illustrate how the incumbent metric (CO_2-equivalent calculated using GWP_{100}), misrepresent the warming of an exemplary f-gas refrigerant (HFC-134a). The model outputs novel profiles of atmospheric concentration, radiative forcing, and temperature, in three scenarios. Scenario A models the response to a positive step change in emissions of the HFC, while Scenario B is the inverse. Scenario C models a reduction of 85% by 2036 of emissions according to targets for high-emitting countries set in the Kigali Amendment. The modelling results evidence that the commonly used CO_2-equivalent with its GWP_{100} does not represent the atmospheric responses, and particularly the warming of the exemplary short-lived HFC. Through the literature review, however, we identify many other metrics available that could be applied for f-gases, and particularly GWP* is recommended to examine in future works. In summary, the paper offers insights into which metrics can best help to identify the effects of f-gases in terms of reducing global warming in a rapid timeframe, and how CO_2-equivalents should not be used as proxy for atmospheric warming in policy discussions.

Introduction & literature review

This paper investigates how metrics used for emissions of fluorinated gas (f-gases) can serve to identify those with the least climate-change impact. F-gases are super-pollutant substances with high Global Warming Potential (GWP) ranging thousands of times that of carbon dioxide (see Fig. 1). The main types of f-gases are hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF6) [1]. In 2019, direct emissions of f-gases were estimated to be 1.4±0.41 $GtCO_2$-eq equating to 2.4% of total greenhouse gas (GHG) emissions [2]. These emissions are surging rapidly as seen by their increase of 250% with respect to emission levels from 1990 [2]. In fact, the growth of HFCs, a type of f-gas, is the fastest amongst GHGs. If left unchecked (e.g. if the phase-down set in the Kigali Amendment to the Montreal Protocol are not achieved), HFCs could become 19% of the global GHG emissions by 2050 [3], posing a threat to the global warming targets set out in the Paris Agreement [4]. At the same time, mitigating short-lived climate

* Corresponding author at: Future of Cooling Programme, Oxford Martin School, University of Oxford, Oxford, United Kingdom.
E-mail addresses: nicole.miranda@eng.ox.ac.uk (N.D. Miranda), giovani.palafox-alcantar@smithschool.ox.ac.uk (P. Giovani Palafox-Alcantar), radhika.khosla@smithschool.ox.ac.uk (R. Khosla), malcolm.mcculloch@eng.ox.ac.uk (M.D. McCulloch).

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Abbreviations and Nomenclatures

Abbreviation

AC	Air conditioner.
α_{rec}	Percentage of refrigerant recovered at end-of-life.
β	Carbon intensity factor.
CFC	Chlorofluorocarbon.
CGTP	Cumuative Global Temperature Potential.
CH_4	Methane.
CMIP	Coupled Model Intercomparison Project
CO_2	Carbon dioxide.
CO_2-eq	Carbon Dioxide Equivalent.
$\Delta T_X(H)$	Temperature changes in time horizon H, following a unit pulse emission of species *X*.
FaIR	Finite-Amplitude Impulse Response.
E	Mass of GHG emissions.
E_{annual}	Annual electricity consumption.
f-gas	Fluorinated gas.
GHG	Greenhouse gas
GTP	Global Temperature Potential.
GWP	Global Warming Potential
GWP_{100}	Global Warming Potential with 100-yr time horizon.
GWP_{20}	Global Warming Potential using 20-yr time horizon.
GWP*	Global Warming Potential-star.
HFC	Hydrofluorocarbon gas
IPCC	Intergovernmental Panel of Climate Change
L_{annual}	Percentual annual leakage.
m	Mass of refrigerant.
n	Lifetime of installation.
^{P}	Pulse emissions.
PFC	Perfluorocarbon
r	Flow parameter of GHG emissions for GWP*.
RCP	Representative Concentration Pathway
S	Step emissions.
s	Stock parameter of GHG emissions for GWP*.
SF6	Sulfur hexafluoride
SLCP	Short-Lived Climate Pollutants
TEWI	Total Equivalent Warming Impact.

Units

°C	Degree Celcius
kt/year	kilotonne per year
mK	mili Kelvin Degrees
mW/m^2	miliWatt per square meter
ppm	Parts per million
ppt	Parts per trillion

pollutants (SLCP) such as HFCs hold the potential to reduce global warming between 0.4 and 0.5 °C by 2050 [3] This is particularly due to many of them having shorter lifetimes than CO_2 (see Fig. 1). To quantify the benefits of controlling such refrigerants and their impact on global warming, clear metrics are required [5].

The consumption and emissions of HFCs are surging due to two main factors. First, the there is an unprecedented increase in the uptake of cooling technologies especially vapour-compressor systems (e.g., air conditioners (ACs), refrigerators and heat pumps), which use HFCs as refrigerants. In fact, cooling devices are predicted to grow 4.5-fold between 2010 and 2050 [6], and are already thought to endanger the achievement of Sustainable Development Goals [7]. HFC used for cooling have emissions through their handling at all phases of their lifecycle. Particularly, the servicing of ACs, and disposal or end-of-life processes have been reported [8] to be the stages were most refrigerants leak [9,10]. To address these leaks and move towards a circular economy of ACs there are initiatives to improve collection rates, increase awareness of the benefits of recycling refrigerants and

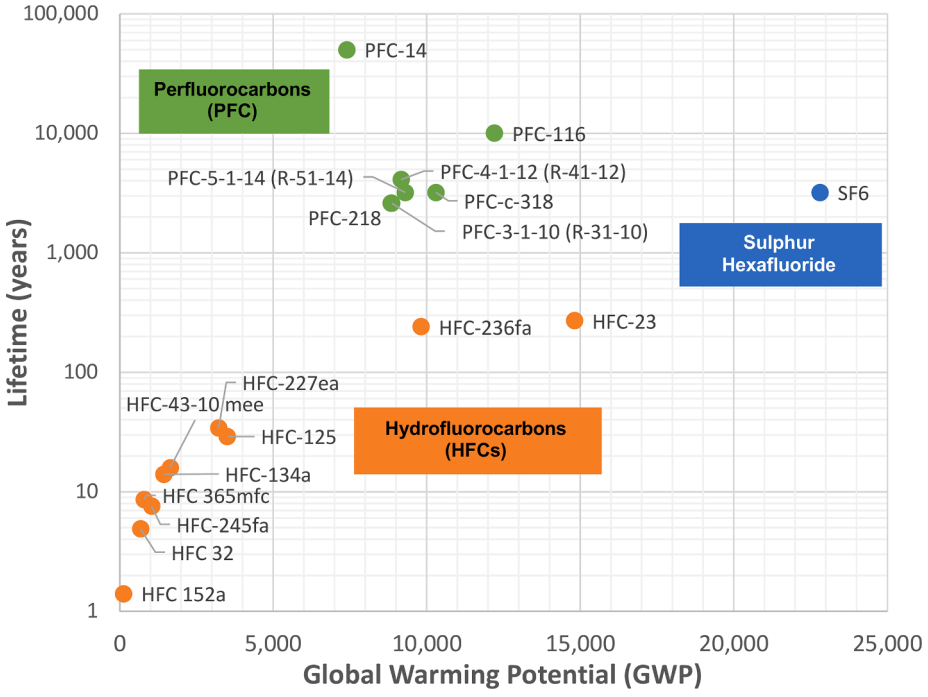

Fig. 1. Common f-gases types: Perfluorocarbons (PFCs, green), Sulphur Hexafluoride (SF6, blue) and Hydrofluorocarbons (HFCs, orange), their Global Warming Potential (GWP_{100}, x-axis) and lifetime in the atmosphere (logarithmic scale on y-axis). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

developing new technologies for recycling refrigerants [11]. These measures have been reported to already show reduction of GHGs, for example, switching to lower GWP refrigerants and more efficient AC systems have reduced emissions from vehicles by up to 70% [12].

The second reason for the use and emissions of HFCs to be increasing is due to the Montreal Protocol (agreed in 1987 by over 200 countries). This protocol committed to end the production of Chlorofluorocarbon gases (CFCs) [6] which were the most common refrigerants, so there was a shifted towards HFCs to replace CFCs [13]. The Kigali Amendment to the Montreal Protocol (agreed in 2016) was set to tackle this fast rise in high-GWP HFCs through lowering and gradually phasing-out HFC consumption (aimed at a total of 80% reduction by 2047) [14,15]. In response, alternative refrigerants to HFCs are gathering momentum [16]. For example, manufacturers are moving production to use natural and/or ultra-low GWP refrigerants [17,18]. Studies analysing natural refrigerants include ammonia [19], hydrocarbons (propane, isobutane and propylene) [12,19–22] and carbon dioxide [23]. Many are commercially available, although the costs and environmental benefits and impacts of these refrigerants remain under examination [23].

Accurately measuring the effect of HFCs over global warming is critical. Suitable metrics to accurately quantify and enable comparison of HFC emissions with respect to other GHGs, and evaluate solutions are needed. In this respect, the Intergovernmental Panel on Climate Change (IPCC) states [2]: *"[…] There are multiple emission metrics and the most appropriate metric depends on the application. […] The choice of a metric, including its time horizon, should reflect the policy objectives for which the metric is applied.*" However, despite this guideline for metric selection, there is a dominant metric in the literature [8,10,24]: the Global Warming Potential (GWP) factors with a 100-year time horizon (GWP_{100}). These factors use carbon dioxide as a reference gas. But it can misrepresent a large GWP of SLCPs, as these remain in the atmosphere for significantly shorter time. Hence, debate on the right emission metric for SLCPs (and HFCs within these) is ongoing in the academic literature [25,26].

This paper contributes to the literature by examining the metrics available for more accurately evaluating the effects of f-gases in terms of their minimal atmospheric warming potential. It is the first to open the discussion on different metrics for f-gases in light of global warming. It also provides novel insights on how the incumbent metric CO_2-equivalent (using GWP_{100}) has failed to represent the behaviour of short-lived f-gases. For this, first, a literature review of emission metrics applied to HFCs and/or to SLCPs is undertaken. Second, HFC-134a emission scenarios are used as an example to compare how their warming potential differ from those of their associated CO_2-equivalent emissions (estimated with GWP_{100}). The emissions are input to the climate model Finite-Amplitude Impulse Response (FaIR) model. It is expected that robust metrics will enable a more accurate assessment of the effect of f-gas emissions over global warming and serve to better evaluate solutions.

Metrics for f-gases and/or short-lived climate pollutants

In selecting from multiple emission metrics, the most appropriate choice depends on the application and policy objectives that it is used for. GHG emission metrics may differ with respect to (i) the key measure of climate change they consider, (ii) whether they consider climate outcomes for a specified point in time or integrated over a specified time horizon, (iii) the time horizon over which the metric is applied, (iv) whether they apply to a single emission pulse, emissions sustained over a period of time, or a combination of both, and (v) whether they consider the climate effect from an emission compared to the absence of that emission, or compared to a reference emissions level or climate state [27]. The IPCC [2] states that *"[…] A metric that establishes equivalence regarding one key measure of the climate system response does not imply equivalence regarding other key measures […]"*. The most common metrics for GHG emission use carbon dioxide as the reference gas and are the GWP, Global Temperature change Potential (GTP), Cumulative Global Temperature Potential (CGTP) and GWP*. By applying these metrics to emissions of non-CO_2 gases they are standardised and then referred to as "carbon dioxide equivalent".

The commonly used GWP metric is based on the properties of a pulse (a unit mass emitted in a short period) of GHG emission to trap heat in the atmosphere in comparison to CO_2. For calculations of emission-equivalents, a time horizon of 100-years can be used as follows [26]:

$$E_{CO_2-eq,100} = E \times GWP_{100} \tag{1}$$

Where E refers to the GHG emissions [27]. Calculating emissions from this metric has been under heavy criticism. It has been argued that is not well-suited for estimating warming effects at specific points in time from sustained SLCP emissions [26]. Because the response of a pulse emission of SLCP decreases over time (for instance, after 20 years), its warming depends more on the rate of emissions at the current time rather than its cumulative emissions over the long term. This is contrary to CO_2 [25] which accumulates in the atmosphere. A great amount of ambiguity on global temperature outcomes results from treating all refrigerant gases interchangeably based on GWP_{100} within the 100-year stated emissions target [28]. For SLCPs, such as HFC gases commonly used in AC and cooling equipment, the average lifetime is approximately 15 years [29]. Because of this short lifespan a GWP over 100 years significantly underplays their warming impacts on the planet's climate over a shorter time scale.

An alternative is to reset the time scale to 20 years. The CO_2 equivalent emissions for GWP_{20} are defined as follows[29]:

$$E_{CO_2-eq,20} = E \times GWP_{20} \tag{2}$$

However, as for the use of GWP_{100} this measure is only refers to emission-equivalence, not a warming-equivalence. In other words, GWPs are for standardising emissions, and this is not extrapolated for standardising warming from those emissions of accumulating gases (which due to different lifetimes can reach new atmospheric concentration-equilibriums). Another metric, the GTP is based on a cost-effectiveness ratio; it weights emissions based on their global warming contribution in a specified future year. This means that as a target year approaches the relative importance of the emissions will increase [30]. However, setting GTP to a static time horizon (e.g., GTP_{100}) would not match well with a cost-effectiveness framework because the year evaluated would not align to the year of peak warming, nor the overall damages caused by each emission [31–33]. A beneficial outcome might be obtained from GTP if a time horizon for GWP is constantly reviewed and updated based on actual emissions and changing climate goals [34]. The CGTP is defined as the ratio of step responses to X to pulse responses to CO_2 [35]:

$$CGTP_X = AGTP^S_X / AGTP^P_{CO_2} \tag{3}$$

where these absolute metrics are defined as $AGTP_X(H) = \Delta T_X(H)$ where $\Delta T_X(H)$ is the temperature changes at time t following a unit pulse emission of species X, and H the chosen time horizon. The P or S superscripts denote metrics based on pulse or step emissions respectively.

The next metric, GWP*, offers a closer resemblance compared to GWP_{100} between cumulative CO_2-equivalent emissions and temperature change [25]. The GWP* effectively equates an increase in the emission of a specific short-lived GHG to a one-off pulse of CO_2. It considers short- and long-term timescale of climate response to changes in radiative forcing due to changes in GHG emissions [36]. Lynch et al. [36] demonstrated several methane (CH_4) and CO_2 emission scenarios with the proposed GWP* metric to display their contrasting dynamics. They compared the results between the typical GWP_{100} and GWP* metrics noting some of the drawbacks of GWP_{100} and how these are overcome by GWP*. GWP* is defined by Cain et al. [25] as the CO_2 warming-equivalent emissions (i.e., the CO_2 pulse-emissions that produce the equivalent radiative forcing than those of the f-gas under inspection):

$$E_{CO_2-w.e._{(SLCP)}} = \left(r \times \frac{\Delta E_{SLCP}}{\Delta t} \times H + s \times E_{SLCP} \right) \times GWP_H \quad (4)$$

where, the r and s values correspond to flow and stock parts of the Equation (4), respectively, and are considered 0.80 and 0.20 for methane (short-lived as many HFCs) and the IPCC's adopted Representative Concentration Pathway (RCP) 4.5 scenario. Collins et al. [37] acknowledge that CGTP and GWP* are similar in terms of structure and conceptualisation. Even though their values differ slightly, their key takeaway is that these metrics should be contrasted with GWP which is inconsistent with current policies, and misinforms SLCP scenarios in which emissions are decreasing [26]. Overall, both step-impulse approach metrics provide a significantly better comparison of SLCPs with long-lived GHGs regarding long-term temperature goals [38].

Another metric for appliances (or systems) using refrigerants suggested by Mota-Babiloni et al. [5] is the Total Equivalent Warming Impact (TEWI). These authors mainly look at GWP_{100}, GWP_{20}, GTP_{100}, GTP_{20}, and TEWI (not GWP*). They report the level of uncertainty for GWP and GTP, and how it increases if the lifetime of a GHG is short. TEWI is defined by Gao et al. [39] as:

$$TEWI = (GWP \times m)((L_{annual} \times n) + (1 - \alpha_{rec})) + (E_{annual} \times \beta \times n) \quad (5)$$

where m is the mass of refrigerant (kg), L_{annual} is the percentual annual leakage of refrigerant, n is the lifetime of the installation (years), α_{rec} is the percentage of refrigerant recovered at the end-of-life, E_{annual} is the annual electricity consumption (kWh), and β is the carbon intensity factor ($kgCO_2$-eq kWh^{-1}). Fischer [40] suggested that the TEWI metric is better applied when there are large differences between the time horizon (e.g., GWP_{100}) and the system lifetime (e.g., 15 years). Makhnatch and Khodabandeh [41] compared metrics in the analysis of a heat pump, and found that GWP yields a higher warming impact than GTP for a 100 years baseline and that the TEWI metric sparked a still inconclusive debate around measuring the real warming impact of cooling appliance [42].

Gap analysis and contribution of this study

The analysis of this section looks at the gap in the refrigerants sector, between existing metrics of carbon foot printing and the needs to understand the true warming potential of f-gases. All the metrics examined have strengths, limitations and uncertainties [2]. No single one is found to accurately simplify the vast complexity of the physical climate system and how it interacts with past, current, and future GHG emissions. However, the successful application of GWP* to methane (another SLCP), makes this metric promising for short-lived f-gases. Particularly, because GWP* surfaces as a strong metric that can estimate emission-equivalents in the short-term and that reflects the actual warming-equivalence of HFCs.

The use of an accurate metric that reflects actual atmospheric warming of a short-lived f-gas could serve, for example, to have a better understanding of the impact of HFC banks worldwide on global warming. HFC banks are physical deposits of these gases, such as the current stock of refrigeration appliances in operation plus landfill sites with cooling equipment. There has been work on the quantification of CFC banks to minimise the impact on the ozone layer [43]. However, there is limited literature found on the effect of HFC banks on global warming, being the most recent the work by Velders et al. [44]. Having a stocktake of HFC banks requires increasingly urgent attention as the these are expected to rapidly increase. Further, a standardised metric such as GWP* could serve to quantifying the impact of different HFC emissions and to assess the scale of solutions. One example of unknown impact of solutions is the positive effects of refrigerant recovering and recycling at the end-of-life to be thermally destroying them safely [45].

The use of an accurate metric could also be applied to assess solutions or transitions between high-GWP refrigerants to more sustainable ones. For example, currently, the most used refrigerant in developed countries is R-410a. R-32 is receiving much attention and it is expected to be a next-generation refrigerant [46,47] given its potential to reduce electricity demand, easy recyclability and one-third lower GWP compared to R-410a. If all R-410a were converted to R-32, the impact of global warming from HFCs in 2030 is estimated to be reduced by the GWP_{100} CO_2-eq of approximately 800 million tons (19%) compared to the continued use of R-410a [48]. Thus, several major manufacturers [49,50] are at the forefront of implementing its use. This is one example of such planned transitions, however, the true effect that they will have on atmospheric warming is not fully accounted for because of the limitations of the CO_2-eq metric – a gap that this paper addresses.

In summary, this literature review evidences the gap of a metric that accurately reflects warming equivalence. Such a metric has not yet been proposed for f-gases used as refrigerants in cooling equipment. The research that evidences (by modelling) that CO_2-equivalent-emissions are not representing the warming from short-lived climate pollutants and that GWP* is correcting this, is found in the work Lynch et al. [36] for methane. For other short-lived climate pollutants such as short-lived f-gases there is no research yet that applies GWP*, regardless of the scientific debates in correcting the CO_2-equivalent (GWP_{100}) estimates [26], and thus is a promising future research area.

Next, the Methods and Materials section compares for the first time (to the authors' knowledge) the atmospheric contributions of short-lived HFC emissions with respect to the associated CO_2 equivalent emissions. The Results and Discussion section illustrates the issues encountered with emission-equivalent metrics and establishes the need for warming-equivalence in the metrics going forward.

Materials and methods

To compare how metrics estimate the warming potential of f-gases, we use the open-sourced Finite-Amplitude Impulse Response (FaIR – Version 1.3) model to simulate a baseline and three emission scenarios [51]. We choose FaIR as it is a simple climatic model that has been validated previously [51] and used for another short-lived climate pollutants (methane) [36]. Zero solar and volcanic forcing are assumed to focus on the anthropogenic f-gas emissions. This emission-based model provides a simple way to assess global warming and is in good agreement with more computationally intensive atmosphere-ocean circulation models (e.g., Coupled Model Intercomparison Project (CMIP) models used by the IPCC).

Fig. 2 show the flow of information to model in FaIR the emission profiles of an HFC and its corresponding CO_2-equivalent. We model the short-lived refrigerant HFC-134a to exemplify the application of the incumbent metric GWP, but it should be noted that FaIR (v.1.3) has available seven additional HFCs (HFC-23, –32, −43–10, −125, −143a, −227ea and −245fa [51]). Emissions of HFC-134a are used because as it is a dominant f-gas in the atmosphere [52], and commonly used as refrigerant in vapour-compressor technologies [53]. Additionally, it is the focus of recent international policy as it has readily-available low GWP alternatives [52].

First, emission profiles according to four scenarios are input to the model. We consider the emissions from the RCP 4.5 pathway scenario as a baseline (blue lines in Fig. 2) because it is an intermediate pathway. The emissions from this baseline are included in the FaIR model package [51]. For the three emission scenarios, we initially add the (increase or decrease) HFC-134a emissions to the baseline emissions of RCP 4.5 and then input the profiles into FaIR (green lines in Fig. 2). The three scenarios are:

1) Scenario A – A positive step change in emissions that adds 1.67 kt/year of HFC-134a to the atmosphere the initial year (chosen to be the 2000, but it should be noted that any starting year would have led to same model results). These emissions correspond to an additional 1% of the HFC-134a global emissions with respect to the year 2010 [52].

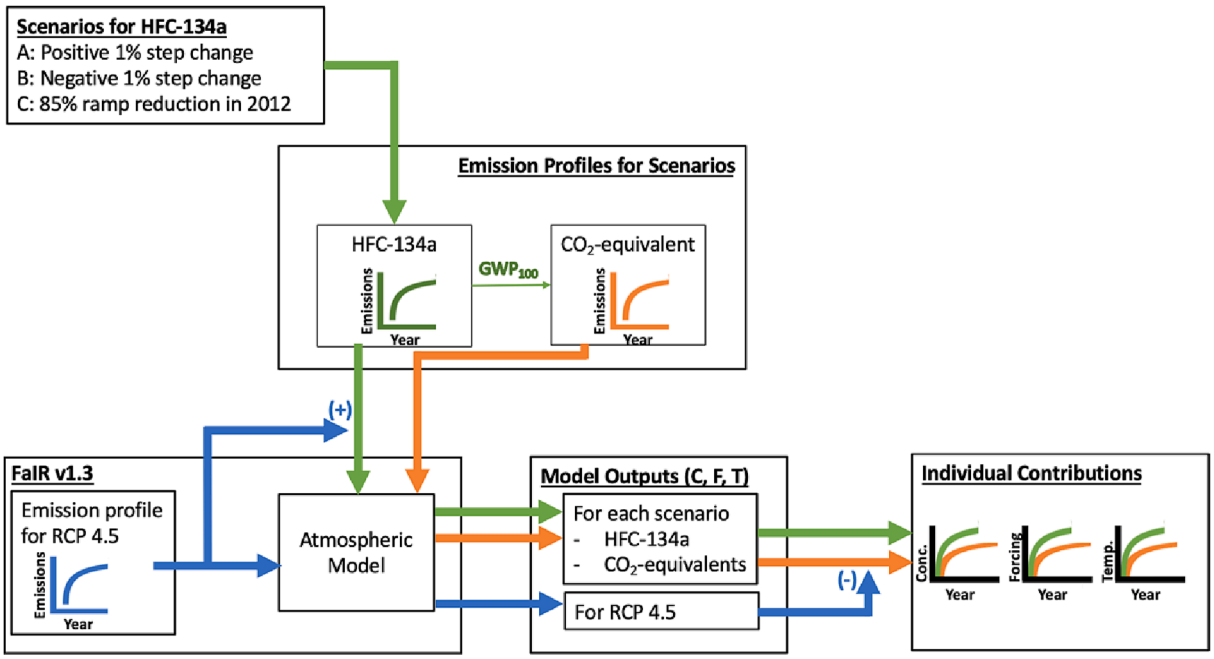

Fig. 2. Flow of information to model the three emission scenarios (A, B and C) and obtain atmospheric concentration (C), radiative forcing (F) and temperature (T). The green lines, indicate the inputs and outputs HFC-134a, the orange lines are for their corresponding CO2-equivalent, and the blue lines are emissions from the RCP 4.5 used as baseline – the (+) and (-) symbols indicate when the inputs and outputs from RCP4.5 were added and subtracted from the green and orange data flows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This amount is solely chosen to examine the behaviour, and is only a fraction of the 250% projected increase in HFC-134a emissions from 1990 to 2019 [2]. The 1% is based on the work of Lynch et al. [36] which also uses this percentage to model another short-lived climate pollutant (methane) through FaIR.

2) Scenario B – A negative step change in emissions, namely, the opposite change than in Scenario A. Thus, 1.67 kt of HFC-134a are subtracted annually from the RCP4.5 scenario from the year 2000 onwards. Although this scenario, as per Scenario A, are small changes, they exemplify how small changes in emissions could change the contribution to global warming.
3) Scenario C – A policy-based scenario in which 85% reduction in HFC-134a emissions from the year 2012 to 2036 are modelled. This is based on the Kigali amendment of the Montreal Protocol [44] for nations including the United States and members of the European Union committed to these reductions and timelines. For this scenario, the global emissions of the year 2012 are considered for HFC-134a. This is 157 kt/year based on the RCP 4.5 scenario. A ramp of slope −5.4 kt/year is the input between 2012 and 2036. This results in the target emissions of 23.6 kt/year (i.e., 15% of those in 2012) from 2036 onwards.

Thereafter, we build profiles of CO_2-equivalent emissions (orange line in Fig. 2) by using the GWP_{100} of HFC-134a for each scenario[1] as per Equation (1) and as shown in the box of Fig. 2 'Emission Profile for Scenarios'. GWP_{100} of 1,534 for HFC-134a is used. The equivalent emissions of CO_2 are also added to the baseline RCP 4.5 emission, before inputting these profiles to FaIR.

The model outputs are atmospheric concentrations (in ppt and ppm for HFC-134a and CO_2, respectively), radiative forcing (i.e., the change in energy flux caused by the emissions in mW/m^2) and changes temperatures (in mK). We report the contributions of the three illustrative scenarios as the differences between their output concentrations, radiative forcing, and temperatures and those of the baseline (RCP 4.5) scenario in the Results section.

Results and discussion

Comparing step-changes of the exemplary f-gas (Scenarios A and B)

Scenarios A and B examine the contribution of positive and negative HFC-134a emission step changes, respectively, to atmospheric concentration, radiative forcing and warming. Baseline emissions are implicit in the model and they correspond to those of the IPCC's RCP 4.5 pathway (see Fig. 2).

Fig. 3 are the results for Scenario A for an increase in HFC-134a emissions.[2] The figure shows (in green lines) what a 1.67 kt/year additional emission per year of HFC-134a would contribute to the atmosphere. It also shows the contributions of CO_2 emissions (orange lines) that are considered "equivalent" by using GWP_{100} in Eq. (1).

For the emissions, as expected, the use of GWP_{100} (in Eq. (1)) acts as a scaling factor and hence, the same shape of profiles for the emissions of HFC-134a and its CO_2-equivalent are inputs to the model. For the atmospheric concentration, forcing and warming, however, there are substantial differences when evaluating the two gases. For atmospheric concentration contribution, HFC-134a increases when the step change occurs, reaching a plateau of 1.28 ppt after 66 years (2066). No overshoot or oscillations are observed in the step-change response. Conversely, the step change in CO_2 emissions progressively increase the concentration of this gas in the atmosphere. The disparity is explained by the lifetime of these gases. Particularly, due to the short lifetime of HFC-134a (14 years), a new steady-state point is reached in which emissions are counteracted by natural atmospheric removals, in other

[1] The metrics used to input of emissions for HFCs and CO_2 into FaIR v.1.3 are different. HFC-134a emissions are input using their mass in kilo-tons (kt). For CO_2, however, emissions are input in giga-ton of carbon (i.e., which is calculated using molecular weights, so that 12 Gt of CO_2, equate to 44 Gt of carbon).

[2] The way of representing this is similar to what Lynch et al. reports for methane. [36].

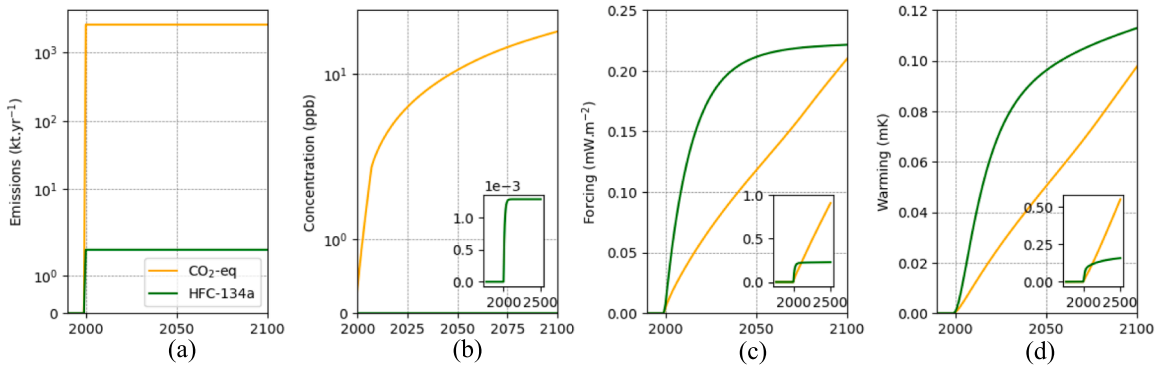

Fig. 3. Scenario A – Comparing the atmospheric response to a positive step change in the year 2000, of HFC-134a emissions (green) and of its related CO_2-equivalent emission (orange), until the year 2100. (a) The negative step-change in emissions. Thereafter, the resulting effect of the step-change over: (b) atmospheric concentration, (c) radiative forcing and (d) temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

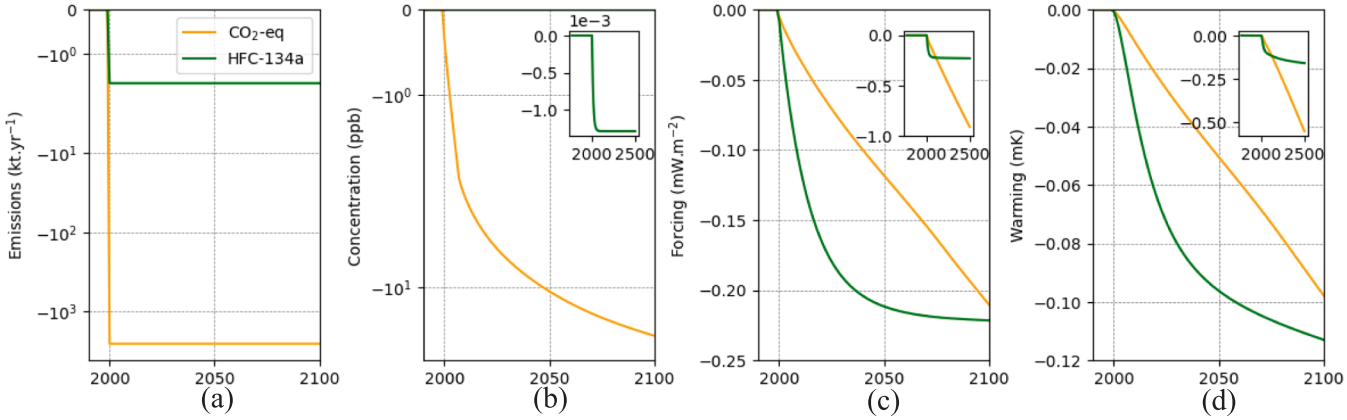

Fig. 4. Scenario B – Comparing the atmospheric response to a negative step change in the year 2000, of HFC-134a emissions (green) and of its related CO_2-equivalent emission (orange), until the year 2100. (a) The negative step-change in emissions. Thereafter, the resulting effect of the step-change over: (b) atmospheric concentration, (c) radiative forcing and (d) temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

words they degrade. This behaviour is not experienced by CO_2 which accumulates in the atmosphere due to its long lifetime.

The different profiles of concentrations resurface in the forcing and warming results. For HFC-134a, over-damped responses are observed for the step-change (i.e., no oscillation surrounding the new steady-state, but slower to reach that steady-state). The radiative forcing increases initially rapidly reaching 0.20 mW/m^2 within 40 years (by 2040). Thereafter, a slower growth reaches a plateau of 0.23 mW/m^2 by 2220. The rapid initial response is noteworthy as it indicates a potential of these GHGs to shape radiative forcing in the short term (with highest impacts in the next 40 years). A similar inflexion point results for the warming contribution of HFC-134a. Within 47 years, the atmospheric warming caused by emissions of Scenario A result in an increase of 0.10 mK. Thereafter, an additional 450 years only furthers the atmospheric warming by 0.06 mK.

The radiative forcing and warming contribution of the equivalent CO_2 emissions is notably different. Both correspond to a steady increase for as long as the emissions are sustained (500 years in the model). For radiative forcing, this corresponds to a ramp of 0.0018 mW/m^2 per year and it intersects with the HFC-134a radiative forcing at 0.22 mW/m^2 in the year 2107. For warming the CO_2-eq has a slope of ~0.001 mK per year and intersects with that of HFC-134a at 0.12 mK in the year 2120. The warming potential is particularly interesting to compare between the HFC-134a and that of its CO_2 equivalent-emission (last column of Fig. 3). It shows that the warming reached in 500 years by CO_2 (0.549 mK) is more than 3 times that of HFC-134a (0.159 mK) in the same period. This could erroneously be interpreted as a lower overall contribution of refrigerants to global warming. However, upon closer inspection of the initial years the results are different. For example, by 2050 CO_2 would contribute 0.050 mK while HFC-134a would almost double with 0.096 mK of global warming. Therefore, the metric chosen to assess the GHG contribution is critical.

Fig. 4 corresponds to the results from a step-change reduction of HFC-134a emissions (-1.67 kt/year) as set in Scenario B. Results correspond to the negatives of those found for Scenario A. These results are of special interest because they illustrate the effect that a small reduction in emissions of HFCs can have over the short-term. Only 1% reduction of HFC-134a could lower warming by 0.080 mK by 2030 and 0.096 mK by 2050. This illustrates that the reduction of f-gases can be a critical contributor to the GHG emission targets. Especially, considering that the Kigali Amendment looks at much larger reductions than 1%, as is be examined by Scenario C. Benefits can be materialised in the short-term, which could contribute to slowing global warming and thus grant time for other long-lived GHG emissions targets to be reached.

Examining f-gas reduction as per Kigali (Scenario C)

The results from FaIR model for HFC emissions of Scenario C are presented in Fig. 5. The profiles resemble those of Scenario B, as they show a large reduction of emissions sought through the Kigali

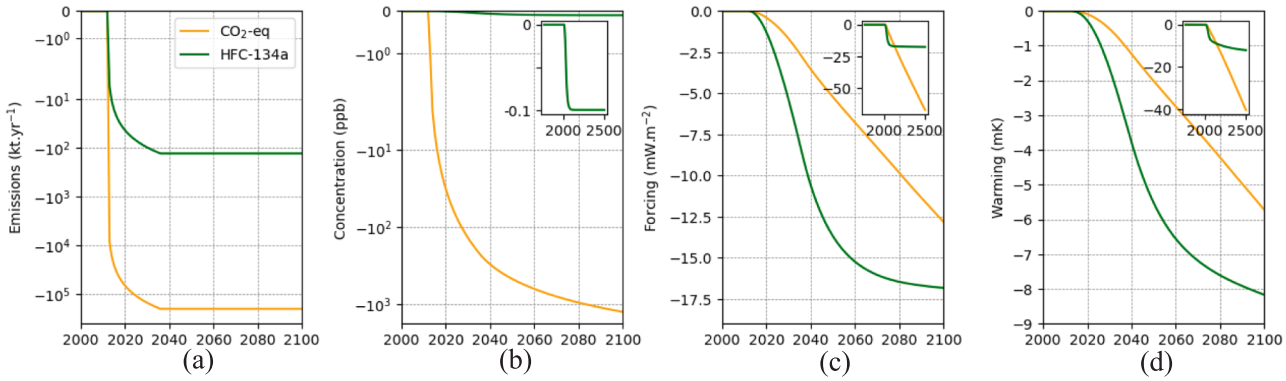

Fig. 5. Scenario C – Comparing the atmospheric response to an 85% reduction of HFC-134a emissions (green) modelled as a ramp of slope −5.4 k/year between 2012 and 2036; and of its related CO_2-equivalent emission (orange), until the year 2100. (a) The emission profiles with such reduction. Thereafter, the resulting effect of the step-change over: (b) atmospheric concentration, (c) radiative forcing and (d) temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Amendment in a short time (24 years). However, the magnitude of change in emissions of Scenario C is more than 80 times that of Scenario B (135 kt/year, compared to 1.67 kt/year, respectively). It reflects the impact of a global effort to reduce HFC-134a.

For atmospheric concentration of HFC-134a, a steep drop is observed for the initial years up to 2100, when it reaches a steady state of −103 ppt (green line). In the context of environmental targets, in 2030 concentrations of HFC-134a would be reduced by 35 ppt, and in 2050 by 86 ppt. Radiative forcing would also plateau by the year 2100, at a value of -16.8 mW/m^2. Its intermediate points of interest are -5.6 mW/m^2 in 2030 and -14.1 mW/m^2 in 2050. For warming potential, Scenario C contributes a reduction of 12.5 mK for the 500 years observed. It does not reach an observable new steady-state, but the temperature declines slower as time increases. It is interesting to note that half of the total decrease (6.2 mK) is obtained by 2054, 42 years after the reduction in emissions commence.

The same analysis for the CO_2 equivalent-emission (see emissions Fig. 5) leads to very different results. This metric over-estimates long-term warming of HFC-134a by 29.1 mK for 500 years after the emission (CO_2-eq warming: 41.6 mK and HFC-134a warming: 12.5 mK). For the short term, under-estimation of the potentials occurs. For example, by the year 2030 the CO_2 warming is -0.5 mK and that of HFC-134a is -1.7 mK. The curve of warming for the HFC-134a and its CO_2-eq intersect at -18.0 mK in the year 2129. Therefore, the CO_2-equivalent emission using GWP_{100} in Eq. (1) fails to capture the short-term behaviour (and benefits) of cutting the HFC emissions.

Comparatively the results from this study with other literature, Allen et al. [26] showed that using GWP* to report the expected warming of HFCs would help reduce it by 28% in 2030. Lynch et al. [36] demonstrated several methane and CO_2 emission scenarios with the proposed GWP* metric to display their contrasting dynamics. Cain et al. [25] argue that the conventional method of using GWP_{100} to convert emissions of different GHG into CO_2-equivalents is not accurate enough, and that a modified GWP* should be used instead. They finally advocate for the use of this new information to incorporate SLCPs into carbon budgets consistent with long-term temperature goals. Xiang et al. [54] found that the emissions of some HFCs including HFC-134a, are increasing more than expected during summer months. The options to replace some HFCs are narrow and are likely to change given the efficiency-capacity trade-off and other properties such as flammability [55].

The findings illustrate that the commonly used metric CO_2-equivalent (estimated with GWP_{100}) does not accurately represents the warming potential of HFCs with short-life span, as the example we used with HFC-134a shows. Therefore, modelling the effect of the emissions of HFC directly offers a way to more accurately estimate warming potential of f-gases (i.e., the key target of international agreements). Furthermore, this analysis provides insights that the achievement of the Kigali Amendment could see benefits in our lifetime, a much shorter timescale than GHG emissions are usually discussed in and better aligned with political cycles. Further efforts in diminishing f-gases could potentially increase the possibilities of helping achieve the goals of the Paris Agreement [13], and allow for extra time to control other long-term GHG emissions [13]. As this analysis makes clear, the mitigation and management of f-gas emissions is an important measure that can more immediately tackle the climate crisis. This paper provides clarity on the way short-lived f-gas refrigerants affect global warming. The results suggest reporting the warming potential of f-gases directly and rather than the CO2-equivalents commonly used. This could help scientists and policymakers to better understand the impact of SLCPs on climate change.

Conclusions

Having better metrics to understand the carbon footprint of f-gases used in refrigerants can serve in identifying successful future policies and to assess solutions. Can we identify the climate-optimum f-gas for use in cooling technologies? Yes, but it is not straightforward. This paper finds that a dominant metric used is CO_2 equivalent-emissions by using GWP_{100}, although it is heavily criticised in the academic literature with alternative metrics proposed. The main reason is that GWP_{100} does not accurately represent the warming behaviour of HFCs with typically short lives (average of 15 years). An alternative, GWP* is an upcoming metric for short-lived gases, which could align emissions with warming-equivalence. However, further research of its application for f-gases is pending. The paper's analysis shows how there is a lack of a suitable metric, and that it is critical to find one to accurately report emissions (e.g., from worldwide HFC banks), but also to measure the effects of transitioning from high-GWP refrigerants to more sustainable ones. Such a metric would hence serve to understand the true effects of implementing policies such as of the Kigali Amendment and the Paris Agreement.

The modelling in this study illustrates that CO_2-equivalent emissions using a GWP_{100} are not suitable within the global warming debates. They do not align with the true warming potential of short-lived gases such as HFC-134a, and many other f-gases. For example, the emission-equivalent metric underestimates the impactful benefits of f-gas reductions for short-term (next 50 years), while overestimating the contribution of these gases in the long-term if increasing their emissions.

Limitation of the modelling is that FaIR (Version 1.3) can only analyse a sample of HFCs, but future work could extend its HFC library. Examining more f-gases can better the understanding of specific emission profiles, for example, those that would result from the detailed

implementation of the Kigali Amendment to the Montreal Protocol. This could be done globally or for specific countries (e.g., where air conditioning is surging). Future work will also examine how the upcoming metric GWP* used to calculate CO_2-equivalent emissions represents the true atmospheric warming of f-gases.

This work has important implications for policy as results suggest proceeding with caution when using CO_2-equivalent emissions for f-gases. Policies can be informed by new and better metrics that are more aligned with the global warming goals. The paper also offers promising insights on the potential of high GWP refrigerants with short lives to reduce global warming in the short term (<50 years). They could play an important role to stay within the international climate and emission targets if action is taken swiftly and well-informed with the right metrics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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