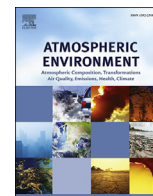




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Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions



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HIGHLIGHTS

- HFC emissions are projected to contribute significantly to future climate forcing.
- New scenarios are formulated for 10 HFCs, 11 geographic regions, and 13 categories.
- Amendment to the Montreal Protocol have been submitted to limit HFC use.
- New regulations in the EU, USA and Japan are projected to reduce HFC emissions.
- The regulations reduce HFC emissions to more than 50% of the amendment proposals.

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ABSTRACT

Hydrofluorocarbons (HFCs) are manufactured for use as substitutes for ozone-depleting substances that are being phased out globally under Montreal Protocol regulations. While HFCs do not deplete ozone, many are potent greenhouse gases that contribute to climate change. Here, new global scenarios show that baseline emissions of HFCs could reach 4.0–5.3 GtCO₂-eq yr⁻¹ in 2050. The new baseline (or business-as-usual) scenarios are formulated for 10 HFC compounds, 11 geographic regions, and 13 use categories. The scenarios rely on detailed data reported by countries to the United Nations; projections of gross domestic product and population; and recent observations of HFC atmospheric abundances. In the baseline scenarios, by 2050 China (31%), India and the rest of Asia (23%), the Middle East and northern Africa (11%), and the USA (10%) are the principal source regions for global HFC emissions; and refrigeration (40–58%) and stationary air conditioning (21–40%) are the major use sectors. The corresponding radiative forcing could reach 0.22–0.25 W m⁻² in 2050, which would be 12–24% of the increase from business-as-usual CO₂ emissions from 2015 to 2050. National regulations to limit HFC use have already been adopted in the European Union, Japan and USA, and proposals have been submitted to amend the Montreal Protocol to substantially reduce growth in HFC use. Calculated baseline emissions are reduced by 90% in 2050 by implementing the North America Montreal Protocol amendment proposal. Global adoption of technologies required to meet national regulations would be sufficient to reduce 2050 baseline HFC consumption by more than 50% of that achieved with the North America proposal for most developed and developing countries.

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1. Introduction

The Montreal Protocol has been very successful in phasing

out the global production and consumption of ozone-depleting substances (ODSs) (UNEP, 2015a). Chlorofluorocarbons (CFCs) have been phased out in developed countries as of 1996 and in developing countries as of 2010, and the use of hydrochlorofluorocarbons (HCFCs) will be phased out almost completely by 2030 in developed and developing countries. In response, the use of HFCs as ODS replacements has increased strongly since the

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mid-1990s for refrigerants and foam blowing agents, medical aerosol propellants and miscellaneous products. HFCs do not deplete the ozone layer (Ravishankara et al., 1994), but are greenhouse gases (Ramanathan, 1975) and therefore contribute to the radiative forcing (RF) of climate. Almost all HFCs currently used as CFC and HCFC replacements have high (100-yr time horizon) global warming potentials (GWPs) ranging from about 150 to 8000 (WMO, 2014). Observations show that the abundances of many HFCs are increasing in the atmosphere (Carpenter and Reimann et al., 2014; O'Doherty et al., 2014; Rigby et al., 2014). In some previous business-as-usual scenario projections, HFCs contribute significantly to climate forcing by 2050 (Gschrey et al., 2011; UNEP, 2014; Velders et al., 2009) with RF values of 0.25–0.40 W m⁻² corresponding to about 9–19% of the RF of CO₂ in 2050 (Velders et al., 2009). Since 2009, the support for global regulations of HFC use has grown significantly. Examples are China and the USA pledging to work together to use the expertise and institutions of the Montreal Protocol to phasedown the production and consumption of HFCs (White House, 2013), followed by expanded support from the G20 nations (G20, 2013); formal proposals to amend the Protocol from North America (Canada, USA, Mexico) (UNEP, 2015b), Island States in the Pacific (UNEP, 2015e), the European Union (EU) (UNEP, 2015c), and India (UNEP, 2015d); and an endorsement by 54 African countries to start formal negotiations to phasedown HFCs (AMCEN, 2015). There are, however, concerns by some countries regarding the availability of alternatives for high-GWP HFCs for countries with high ambient temperatures (UNEP, 2015f).

National (Japan, USA) and regional (EU) regulations have been implemented recently to limit the use of high-GWP HFCs. The EU mobile (or motor vehicle) air conditioning directive (MAC) (EU, 2006) bans the use of HFC-134a (GWP = 1360 (WMO, 2014)) in motor vehicle AC from 2017 and the revised F-gas regulation (EU, 2014) places bans on the use of certain high-GWP HFCs in other sectors starting in 2015 and also contains a phasedown of HFC consumption from a base level. In the USA (US-EPA, 2012) there are economic incentives to eliminate HFCs for mobile AC use and there are new regulations (US-EPA, 2015) to further limit the use of high-GWP HFCs in the USA and other countries. Similar new regulations are in place in Japan (METI, 2015).

If the future growth in the use of high-GWP HFCs is to be limited and HFC use ultimately phased down under regulations or treaty obligations, alternative technologies and/or substances will be required to meet the increasing global demand expected for applications that use HFCs, including refrigeration, air conditioning, foam blowing, as well as other applications that traditionally used CFCs and HCFCs. The continued development and marketing of new technologies and substances (UNEP, 2014) are expected to lower climate forcing from sectors that now use high-GWP HFCs. At present, developed countries have already shifted from HCFCs to high-GWP HFCs in many applications and developing countries are beginning to shift from HCFCs to high-GWP HFCs, although alternatives for high-GWP HFC uses are being developed and deployed for most applications. It is important to note that many applications currently using high-GWP HFCs consume significant amounts of electrical energy resulting in CO₂ emissions associated with electricity generation contributing far more to long-term climate forcing than the HFCs emitted over the application lifetime. Thus, energy efficiency is a critical consideration in choosing technologies replacing high-GWP HFCs. Two quantitative examples of the importance of energy efficiency on the overall climate impact of HFCs and alternatives are discussed below. Energy efficiency is not incorporated in the scenarios themselves, since the necessary information is unavailable for most use sectors, world regions, and diverse ambient conditions.

Projecting the future abundance and radiative forcing of HFCs in the atmosphere has become more complex in light of the diversity of national and regional regulations, formal proposals to amend the Montreal Protocol, and a greater recognition of the diversity of future HFC demand from countries with different climates, population projections, and technological readiness. In an effort to inform decisions related to future HFC use and regulations, we present here new scenarios of HFC growth that are specific to use sectors and geographic regions and include estimated climate forcing contributions. The inclusion of more detailed and comprehensive data for different use sectors and regions increases confidence in projected HFC emissions in coming decades and in estimates of the effectiveness of existing and proposed control measures. The new scenario methodology is an essential tool to translate HFC control measures aimed at future production and consumption into timelines of HFC atmospheric abundances; it is the latter that ultimately influence climate through radiative forcing. The new baseline scenarios are illustrative rather than prescriptive of future HFC use and emissions because a wide range of assumptions is required to generate them. The following sections present the scenario methodology; the GWP-weighted emissions and radiative forcing results by sector and region; modified scenarios based on proposed control measures; alternatives to high-GWP HFCs; and energy efficiency considerations.

2. HFC baseline scenarios

The new HFC baseline scenarios can be qualified as business-as-usual scenarios because they assume (as in previous work (Velders et al., 2009)) that current uses (substances and technologies) of HFCs for specific sectors continue unabated and that developing countries follow the same transitions from HCFCs to HFCs and not-in-kind (NIK) alternatives as has occurred in developed countries. Our baseline scenarios provide a primary point of reference to evaluate the need for, and impact of, alternative technologies. Indeed, alternative technologies are included implicitly to varying extent in the national regulations (see Section 5). The new scenarios improve upon Velders et al. (2009) by incorporating more specific information that allows detailed projections of HFC use by sector and region. The principal information sources are: 1) robust historical HFC consumption data by sector for developed countries derived from their United Nations Framework Convention on Climate Change (UNFCCC) National Inventory Submissions (UNFCCC, 2014); 2) historical HFC consumption data for China with some additional data for other developing countries; 3) data for historical HCFC consumption from UNEP (2015a), part of which has been replaced by HFCs; 4) scenarios of Gross Domestic Product (GDP) and population from Shared Socioeconomic Pathway (SSP) projections (O'Neill et al., 2012); and 5) observed atmospheric abundances of HFCs from 1990 to 2013 used as constraints on the historical consumption data. From these datasets HFC consumption is derived from 1990 to 2050 for 11 countries/regions and 13 separate uses (see caption of Fig. 1 for details), and 10 HFCs (HFC-32, -125, -134a, -143a, -152a, -227ea, -236fa, -245fa, -365mfc, and -43-10mee). In contrast, Velders et al. (2009) considered only two regions (developed and developing countries) and three sectors (See the Supplementary Material (SM) for details about the scenarios and methods of calculating consumption data, emissions, and concentrations).

The UNFCCC prescribes guidelines for a common and consistent basis in reporting total greenhouse gas emissions in order to determine whether countries are meeting their emission reductions targets under the Kyoto Protocol. The detailed underlying inventory information on stocks provides a consistent time series of HFC use by sector and a starting point for projections, especially

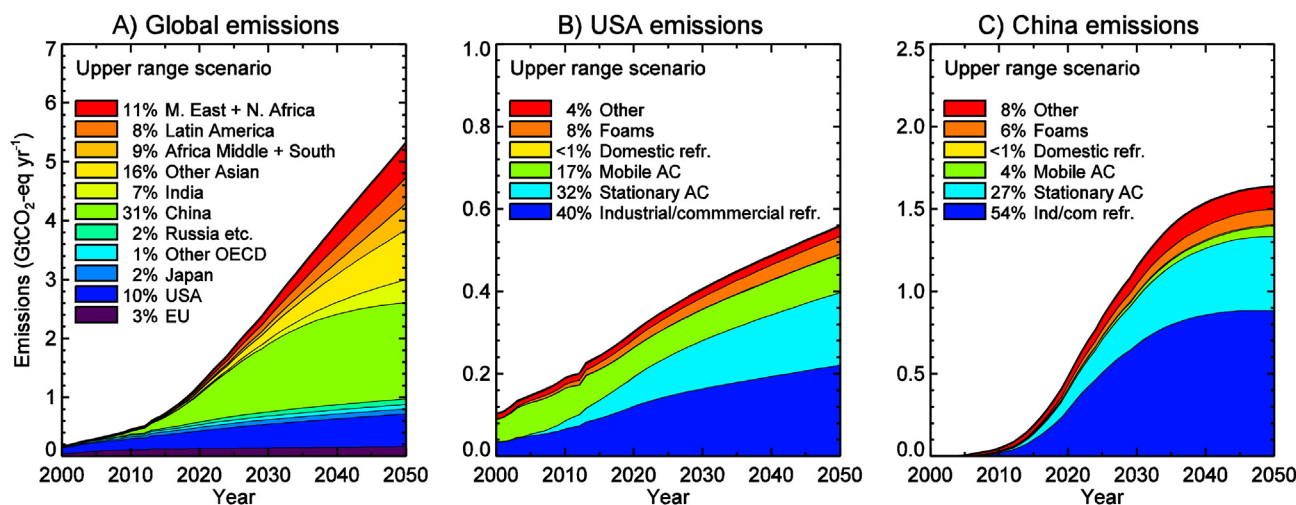


Fig. 1. Contributions of use sectors to HFC emissions ($\text{GtCO}_2\text{-eq yr}^{-1}$ and percent) in three selected regions in the upper range of the baseline scenario. Note differences in the vertical scales. USA (B) has the largest historical emissions and China (C) has the largest projected emissions. Panel A shows the global emissions. The percentages refer to the relative contributions of the GWP-weighted emissions in the upper range in 2050. See Fig. S4 for an overview of the HFC emissions in all 11 regions (EU, USA, Japan, other OECD countries, States of the former Soviet Republics and Yugoslavia (Russia), China, India, other Asian countries, Middle and Southern Africa, Latin America, and Middle East and Northern Africa). In total, 13 separate uses are aggregated into 6 groups as (1) industrial, commercial (open compressor), commercial (hermetically sealed compressor), and transport refrigeration; (2) stationary AC; (3) mobile AC; (4) domestic refrigeration; (5) foams: extruded polystyrene (XPS), polyurethane (PUR), and open cell foams; and (6) other: aerosol products; fire extinguishing systems; and solvents. See Table S1. In the scenarios the lifetimes, GWPs and radiative efficiencies of WMO (2014) are used. The 100-yr GWPs of HFC-32, -125, -134a, -143a, and -152a are, 704, 3450, 1360, 5080, and 148, respectively.

when constrained by atmospheric measurements. Developed countries annually submit emissions and activity data to UNFCCC as part of their National Inventory Submission. The so-called Common Reporting Format (CRF) files contain data on: HFCs incorporated into new manufactured products; HFCs in operating systems (average annual stocks); HFCs remaining in products at decommissioning; and emissions of HFCs originating from each of these sources. HFC specific data are available for each year from 1990 to 2012 for all refrigeration and air conditioning (AC) sectors and in part for other sectors. In the present analysis, annual, country, sector, and HFC specific consumption data are derived from the CRF data. The annual consumption is estimated from the change in the annual HFC stock for a sector plus the total annual emissions from all three of the above-mentioned sources. This approach works well for refrigeration and stationary and mobile AC sectors, but data on foams and other sectors are often not available in enough detail in the CRFs. For these sectors the consumption is estimated based in part on emissions inferred from observed abundances. Effective emission factors for each country, sector, and HFC are also derived from the total emissions (from manufacture, service, stocks and disposal) and the amounts in stock (see Table S1). These emission factors are used in calculating emissions from the new scenarios of HFC consumption.

UNFCCC/CRF data are not available for developing countries, which historically have much smaller HFC consumption than in developed countries. However, in recent years HFC production and consumption in China has increased rapidly. Chinese HFC consumption is reported for 2005–2009 (Zhang and Wang, 2014) and for 2010–2012 (ChinaIOL, 2015; Fang et al., 2015) showing increases of 20–40% per year and is used for this analysis. Fluorocarbons contained in exported equipment are separately accounted for in order to derive what is actually used in products and equipment that remain in the country. Part of the derived Chinese HFC consumption is exported in equipment, such as stationary AC (ChinaIOL, 2015). The current magnitude of this export is uncertain and how it will develop in the future even more so, but not taking it into account results in an overestimation of the current national HFC use and future growth attributable to China's domestic use.

Based on information from the Montreal Protocol Technology and Economic Assessment Panel (TEAP) we assume that 20% of the Chinese HFC consumption (ChinaIOL, 2015) for refrigeration, stationary and mobile AC and aerosol product applications is exported and subtract that amount from the national consumption data. In other developing countries, historical HFC consumption is taken into account only for mobile AC and domestic refrigeration (see SM).

For other developing countries, HCFC consumption is projected from 2013 to 2050 using the data already reported under the Montreal Protocol as the starting point and the country/region specific GDP from the SSP scenarios for scaling future use (range of 0.5–8.5% per year) (O'Neill et al., 2012). Then it is assumed that the differences between the projected HCFC consumption and the Montreal Protocol phaseout limits is met for refrigeration, AC, and foam applications by using HFCs and NIK substances and technologies with the replacement pattern as observed in developed countries (Table S2). This new HFC consumption is then added to the projection of existing HFC consumption, mainly HFC-134a for mobile air conditioning, to yield the HFC scenarios for these countries.

The HFC consumption in developed countries starts with the historical HFC consumption as derived from the UNFCCC/CRF data for each country from 1990 to 2011, with an extrapolation to 2012. In the scenarios the consumption grows proportional to the country specific population from the SSP scenarios (range of -1 to $+1\%$ per year) from 2013 to 2050 (O'Neill et al., 2012). The HCFC phaseout is already completed in the EU and near completion in other developed countries (UNEP, 2015a). In the scenarios it is assumed that the full remaining HCFC consumption in the developed countries in 2013 is replaced by HFC consumption. Therefore, to account for the final phaseout of HCFCs, the HFC consumption in the refrigeration and stationary AC sectors is further increased annually from 2013 to 2020 by 4% in the USA, 3% in Japan, 7% in other developed Organisation for Economic Co-operation and Development (OECD) countries (excluding the EU), and 9% in Russia. These increases effectively convert all 2013 HCFC consumption (UNEP, 2015a) to HFCs by 2020, ignoring possible

increased use of alternatives for high-GWP HFCs in this period.

In the IPCC Special Report on Emissions Scenarios (SRES) (IPCC, 2000), used in the previous analysis (Velders et al., 2009), GDP and population data are available only for four regions, while the SSP scenarios are available for 32 countries/regions, which are aggregated to 11 countries/regions for this study. IPCC/SRES has four scenarios for GDP and population, while the SSPs has five scenarios, each quantified by three groups. In this analysis, we use the five datasets (SSP1 to 5) quantified by the OECD as illustrative SSPs as recommended on the International Institute for Applied System Analysis (IIASA) website (O'Neill et al., 2012). For our HFC scenarios, SSP5 is the upper range scenario and SSP3 is the lower range scenario. Technological developments are not driven by environmental concerns in these SSPs and hence are not taken into account in the formulation of our HFC baseline scenarios.

An important aspect of the baseline scenarios is the assumption of market saturation that limits growth in consumption in developing countries. The sum of HFC and HCFC consumption per capita in a developing country is assumed not to exceed the maximum consumption per capita in developed countries. After saturation is reached consumption in each use sector follows the growth or decline in population in a country or region. This saturation of demand is applied to six sector groups individually, i.e., domestic refrigeration, industrial and commercial refrigeration, stationary AC, mobile AC, foams, and other sectors (see Fig. 2).

Emissions are calculated for each sector and region from the HFC consumption data and emission factors using a box model that can be constrained by observed atmospheric abundances of individual HFCs as well as HFC atmospheric lifetimes that account for the chemical removal of HFCs from the atmosphere (Harris and Wuebbles et al., 2014; Velders and Daniel, 2014) (see SM). The unconstrained global emissions (emissions derived mostly from UNFCCC data) for 1990 to 2012 slightly underestimate the emissions inferred from observed abundances for HFC-32, -125, and -134a (see SM Fig. S1); the 2012 unconstrained emissions of HFC-32, -125, -134a are underestimated by 14%, 17%, and 5%, respectively. For HFC-143a the underestimation is largest, about 30% in 2012. The emissions inferred from observed abundances and those derived from reported country data both have uncertainties. The former depend mainly on the uncertainties in the HFC lifetimes,

which are estimates at about 20% (SPARC, 2013), and are likely smaller than the uncertainties in the reported data. We therefore correct for these differences by adjusting the consumption values from 1990 to 2012 in the baseline scenario upwards so that the global emissions are in agreement with emissions inferred from observed abundances from 1990 to January 2013 (Carpenter and Reimann et al., 2014). These adjustments distributed over all sectors and regions (see SM) result in larger HFC consumption and emissions before 2020 followed by only small increases past 2020 when saturation begins to limit HFC growth. For the other HFCs considered here that have lower emissions and less complete consumption data, the box model results derived from atmospheric observations are used in the scenarios.

Recent studies (Lunt et al., 2015; Montzka et al., 2015) concluded that developed country emissions as reported to the UNFCCC account for only about 50% of the total emissions as inferred from observed abundances and that a significant part of the remaining gap is likely due to emissions from developing countries. This conclusion is in agreement with results using our box model. HFC consumption in developing countries, especially in China, has increased considerably in recent years and closes most of the gap between the emissions from developed countries and total emissions from the constrained box model.

In the scenarios discussed here, HFC-23 is not considered since it has very minor product uses and its emissions arise mainly as an unwanted by-product from the production of HCFC-22.

3. GWP-weighted emissions and radiative forcing of HFCs

The contribution of HFCs to climate change is expressed here in terms of CO₂-equivalent (CO₂-eq) emissions and RF. CO₂-eq emissions are HFC emissions weighted by the respective GWPs (100-yr time horizon) (WMO, 2014), while RF values are derived from modelled HFC atmospheric concentrations multiplied by the radiative efficiencies (WMO, 2014). See SM section S5 for details about the calculations.

In the baseline scenarios in 2050, GWP-weighted HFC emissions are 0.8–1.0 GtCO₂-eq yr⁻¹ for the developed countries and 3.2–4.4 GtCO₂-eq yr⁻¹ for the developing countries, resulting in a global total of 4.0–5.3 GtCO₂-eq yr⁻¹ (Fig. 2B). The upper and lower

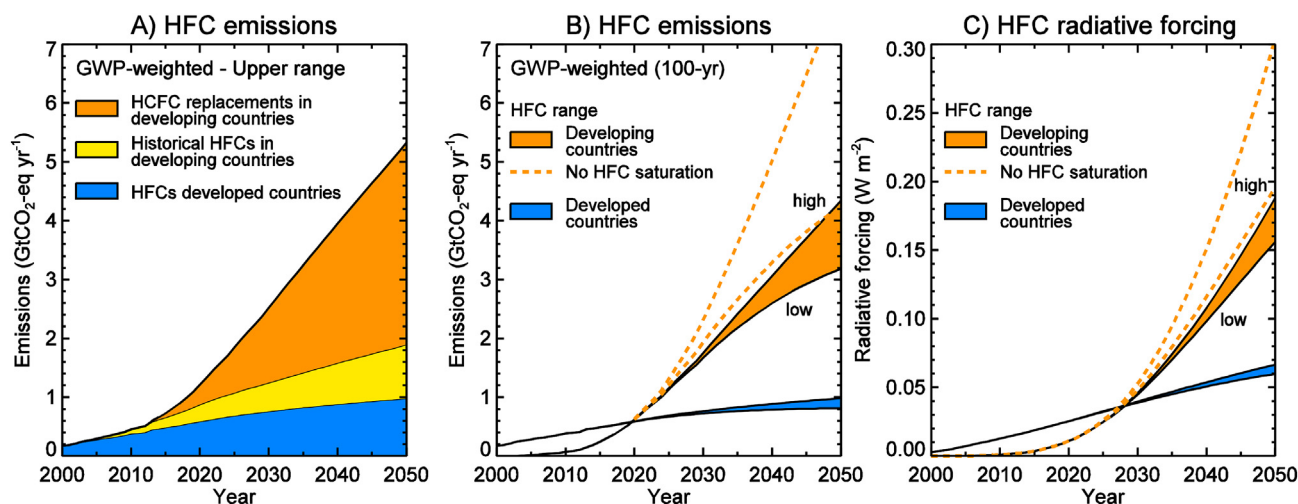


Fig. 2. HFC emissions (GtCO₂-eq yr⁻¹) (A, B) and radiative forcing (C) for the upper and lower baseline scenarios. The HFC emissions are the sum of contributions from consumption in developing (A5) or developed countries (non-A5). The contribution from developing countries in A is split into that from historical HFC production (1990–2012) and its projection (starting in 2013) and that from replacement of HCFCs (starting in 2013). Ignoring saturation of HFC consumption in developing countries increases 2050 emissions from 3.2–4.4 to 4.2–7.9 GtCO₂-eq yr⁻¹ (B) and the 2050 RF contribution from 0.16–0.19 to 0.20–0.30 W m⁻² (C). In 2050 in developed countries, emissions are 0.8–1.0 GtCO₂-eq yr⁻¹ and the RF contribution is 0.06–0.07 W m⁻².

ranges span the results from using growth factors from all five SSPs scenarios. These emissions are lower than the 5.5–8.8 GtCO₂-eq yr⁻¹ in 2050 in Velders et al. (2009), especially for the upper range value. The decrease is mainly the result of using SSP scenarios for GDP and the way the saturation in consumption is applied. Without applying saturation of HFC consumption in developing countries, total HFC emissions are far larger (5.0–8.9 GtCO₂-eq yr⁻¹) in 2050 (Fig. 2B). In Velders et al. (2009), HFC scenarios were estimated for developing countries as a single group, while developing countries now are grouped into six countries/regions using the SSP scenarios. Of the developing countries, the largest projected HFC consumption is in China based on its current HCFC and HFC consumption and large projected GDP growth. Since the current HCFC consumption per capita in China is about twice that of developing countries as a group, HFC saturation in China occurs earlier than in other developing countries and represents the largest factor in reducing estimated emissions below those of Velders et al. (2009) (see Fig. 2B). Consequently, the HFC RF in 2050 in the new baseline scenario of 0.22–0.25 W m⁻² (Fig. 2C) is also lower than the 0.25–0.40 W m⁻² of Velders et al. (2009). The HFC RF in 2050 is comparable to the RF of all ODSs in 2015 of about 0.3 W m⁻² (WMO, 2014).

The ranges in consumption, emissions, and RF shown in Fig. 2 derive directly from the ranges in GDP and population in the SSP scenarios. Additional uncertainty in the HFC scenarios is estimated to be comparable or larger than this range since it must include uncertainties in the future demand for HFCs and the assumption for saturation of consumption in developing countries (Fig. 2B,C); HFC use in new or emerging use sectors, such as industrial and commercial refrigeration in developing countries (see footnote Table S2); and the increasing use of low-GWP alternative substances and NIK technologies (Table S2). These sources of uncertainty are difficult to quantify at present.

The projected emissions in the new baseline scenarios (Fig. S2) are close to those derived from the recent business-as-usual scenario of the TEAP (UNEP, 2014), which goes through 2030, slightly higher than in other sector specific scenarios (Gschrey et al., 2011), and significantly higher than in the Representative Concentration Pathways (RCPs) scenarios (Meinshausen et al., 2011). The latter two scenarios have different assumptions for the HCFC replacement pattern and/or different growth rates for HFC applications. In GtCO₂-eq comparisons of the new HFC scenarios with those for CO₂ in the RCP6 and RCP8.5 (business-as-usual) scenarios, HFC emissions are 5%–11% of CO₂ emissions in 2050. In comparisons of projected growth the 2015 to 2050 increase in HFC emissions is 9%–29% of that for CO₂ over the same time period in the RCP scenarios. Similarly, the HFC RF in the new baseline scenarios is 6%–9% of CO₂ values in 2050, while the increase from 2015 to 2050 is 12%–24% of the CO₂ RF increase.

Fig. 2B shows that historically HFC use has occurred predominantly in developed countries and that future use is dominated by developing countries. Beyond the 2012 starting points in the baseline scenarios, total HFC emissions are comprised of projections of this historical use plus the use in developing countries resulting from the required replacement of HCFCs (Fig. 2A). For developing countries, this replacement growth is about three times the growth in historic use by 2050, both in terms of emissions and consumption. This indicates that any decisions or events that alter the effective HCFC replacement pattern from that assumed here (Table S2) potentially have a large influence on the future HFC contribution to climate forcing.

4. HFC contributions from geographic regions and use sectors

In the baseline scenarios, individual HFC contributions from

each region and each sector are calculated separately in order to estimate annual consumption, emission, bank, atmospheric abundance, and RF values. Currently, the USA contribution to global HFC emissions is largest, but in the baseline scenario China is projected to become the largest before 2020 and reaches 31% of total GWP-weighted emissions in the upper range scenario by 2050 (Fig. 1). USA emissions are projected to fall to about 10% of global emissions by 2050. See SM Figs. S3 and S4 for sector contributions in all 11 regions. Contributions to global emissions from other developing countries are large as well with 23% from other Asian countries (other than China, but including India) and 11% from the Middle East and Northern Africa in the baseline scenarios. In all countries or regions, the largest contributions come from industrial and commercial refrigeration (40–58% by 2050), followed by stationary AC (21–40% by 2050). Historically, mobile AC has been responsible for the largest fraction of HFC emissions and is projected to be 10–18% of developed country emissions by 2050. In developing countries, mobile AC contributes only 3–12% of total HFC emissions in 2050 because of the larger projected growth in refrigeration and stationary AC. The contributions from other sectors to total HFC emissions in each country/region are around 1% for domestic refrigeration, up to 8% for foams and up to 8% for other sectors combined (solvents, aerosol products, and fire extinguishing systems). Projected future use of solvents, aerosol products, and fire extinguishing systems in developing countries (except China) is assumed to be zero because no historical HFC use records are available. A similar ranking of sector contributions is found in 2050 for global consumption, bank, emission, and RF values as presented in Fig. S5, while the contributions of the individual HFCs to consumption, emissions and RF are presented in Fig. S6. More than 90% of the projected HFC RF in 2050 is attributable to combined emissions of HFC-143a, -134a, 125, and -32. It is worth noting that in 2050 the size of the HFC bank contained in refrigeration, air conditioning, foam, and fire protection products is about ten times total annual emissions. The HFC bank therefore represents a substantial source of emissions and RF beyond 2050 (Velders et al., 2014).

5. National and regional regulations for HFC reductions

The new methodology used to formulate the baseline scenarios, constrained by reported HFC use data and tailored to be specific to regions and use sectors for each HFC, represents a tool to evaluate the sensitivity of future HFC climate forcing to proposed and existing HFC regulations. The implementation of selected regulations in the new baseline scenarios (with assumptions outlined in Table S4) alters the annual time series of emission, consumption, bank, and RF values as shown in part in Figs. 3–5 and S7–S10. With the implementation of these regulations the demand in a use sector remains the same, but is met by different substances or advanced technologies.

In the EU, the 2006 MAC directive (EU, 2006) and 2014 revised F-gas regulation (EU, 2014) prohibit use of high-GWP HFCs in certain sectors. For example, the current use of HFC-134a (100-yr GWP of 1360) (WMO, 2014) is banned in all “new type” automobile models effectively since 2013 and in all new automobiles by 2017, and must be replaced with refrigerants with a GWP less than 150. The use of high-GWP HFCs is banned in most stationary refrigeration equipment by 2022 and in many stationary AC applications by 2025. In addition to these bans, there is a HFC phasedown schedule reducing the amounts placed on the market starting from a cap at the 2009–2012 average in 2015 and reaching a 79% reduction in 2030 relative to that average (GWP-weighted). It is important to note that, as for consumption defined under the Montreal Protocol, HFCs contained in exported products are included in this phasedown. This inclusion very likely will drive even more applications to low-

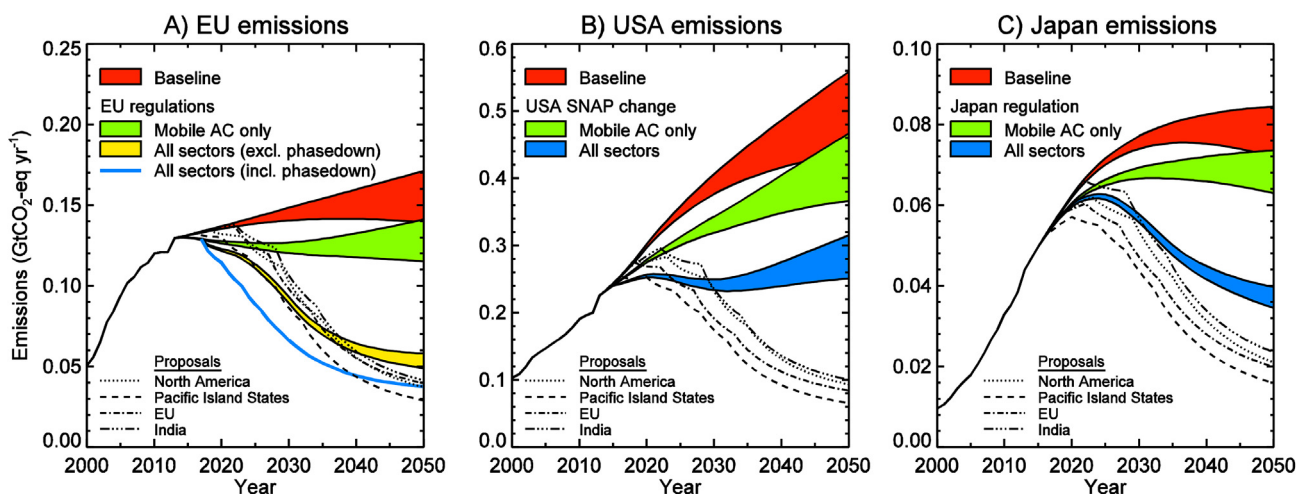


Fig. 3. Response of emissions (GtCO₂-eq yr⁻¹) to implementation of existing HFC regulations in the EU, USA, and Japan. The baseline scenario is from this analysis with the red shading showing the upper/lower range. The panels show the effects of the EU F-gas regulation and EU MAC directive on EU emissions (A), the SNAP changes on USA emissions (B), and the Japanese regulations on Japan emissions (C). Also shown (dashed lines) are the emissions corresponding to the Montreal Protocol amendment proposals. See Figs. S7 and S8 for complementary figures with consumption data and RF. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

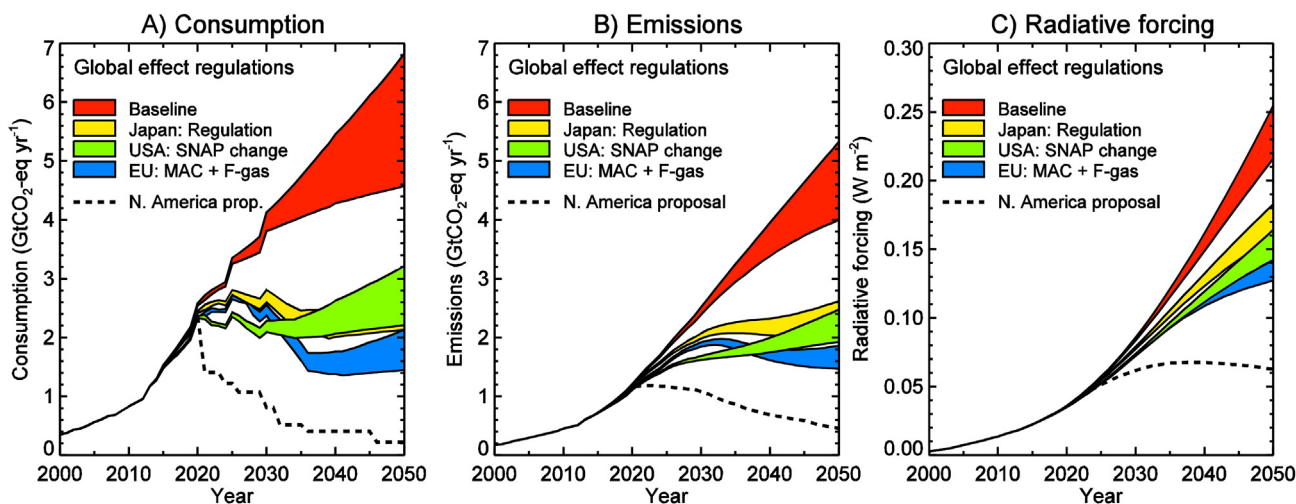


Fig. 4. Response of global HFC consumption and emissions (GtCO₂-eq yr⁻¹) and global RF in the baseline scenario to global implementation of three national regulations and proposals. In each case, the regulation or proposal is applied to all countries, with a five year delay of the regulations for developing countries. Also shown (dashed lines) are the responses to the North America proposal to amend the Montreal Protocol.

GWP alternatives and force technology changes outside the EU.

The EU MAC directive is estimated to reduce HFC emissions from the EU in the baseline scenario by 0.02–0.03 GtCO₂-eq yr⁻¹ (or about 17%) by 2050. EU bans in other sectors reduce the emissions by another 0.07–0.08 GtCO₂-eq yr⁻¹ (about 48%) by 2050, while the additional phasedown provides an extra reduction of 0.01–0.02 GtCO₂-eq yr⁻¹ (about 10%) by 2050. Thus, the emission reductions from the bans are far larger than from the additional phasedown. The total annual reduction is about 0.10–0.13 GtCO₂-eq yr⁻¹ (about 75%) by 2050 (Fig. 3). The total cumulative reduction in emissions, relevant for climate forcing, from the EU regulations is 2.2–2.5 GtCO₂-eq over the 2015–2050 period (Table S6). The total reductions depend somewhat on the assumptions of how many sectors are included (see SM).

The USA has already implemented incentive credits for use of low-GWP refrigerants (US-EPA, 2012) in support of greenhouse gas emission standards for light duty vehicles and removed certain

high-GWP HFCs from the Significant New Alternatives Policy (SNAP) list of allowable technologies for specific sectors in 2015 (US-EPA, 2015). The changes to the SNAP list ban the use of many high-GWP HFCs in, for example, commercial refrigeration applications, such as supermarket systems and vending machines, beginning during the period 2016–2020 and in mobile AC from model year 2021. The implementation of the new SNAP list is estimated to reduce baseline USA HFC emissions by 0.18–0.24 GtCO₂-eq yr⁻¹ (about 43%) by 2050, of which 0.07–0.09 GtCO₂-eq yr⁻¹ (about 16%) comes from mobile AC (Fig. 3). The reduction in 2015–2050 cumulative emissions is 4.6–5.4 GtCO₂-eq.

Japan adopted a regulation in 2015 to limit the use of high-GWP HFCs for specific sectors (METI, 2015). For example, in the regulation, the average 100-yr GWP of refrigerants used in most stationary AC equipment is limited to be below 750 from 2020, in mobile AC below 150 from 2023, and in certain commercial refrigeration equipment below 1500 from 2025. The Japanese

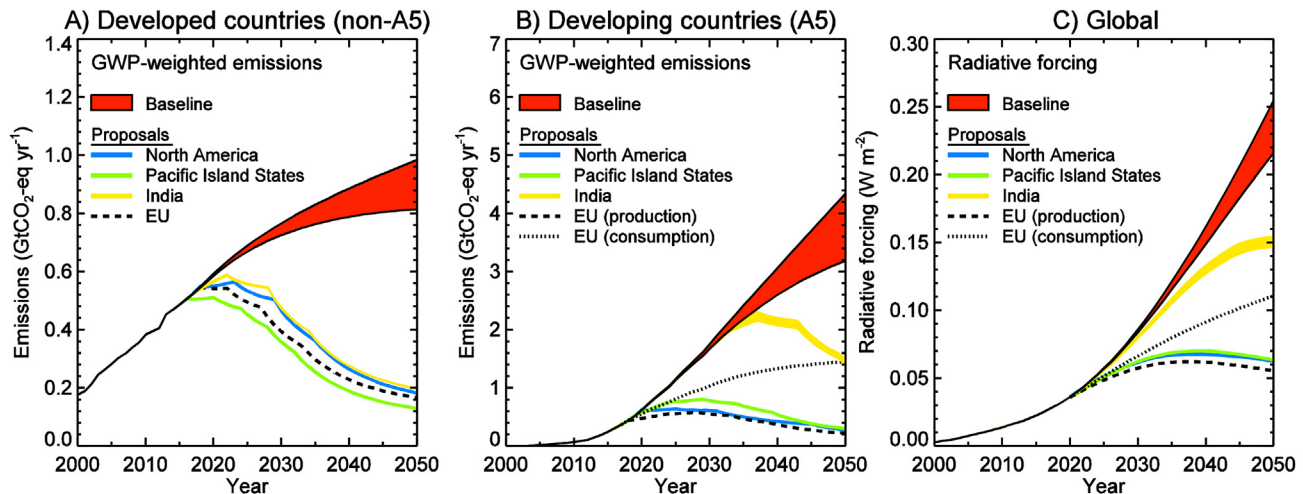


Fig. 5. Response of HFC emissions ($\text{GtCO}_2\text{-eq yr}^{-1}$) in the baseline scenario for developed (A) and developing (B) countries to implementation of Montreal Protocol amendment proposals to regulate HFC use, and the response of global RF (C). The specifications and assumptions underlying the individual scenarios for developed and developing countries in the North America, Pacific Island States, EU and India proposals are outlined in Table S7. The developing country and global emissions from the EU proposal (B, C) are considered upper limits since the proposal does not yet include the reduction schedule for developing country consumption that is expected to be agreed upon by 2020 (UNEP, 2015c). See Figs S9 and S10 for complementary figures for consumption and emissions and Tables S9 and S10 for the reductions in cumulative consumption and emissions.

regulations reduce national HFC emissions by about $0.04 \text{ GtCO}_2\text{-eq yr}^{-1}$, or about 52%, by 2050, of which about $0.01 \text{ GtCO}_2\text{-eq yr}^{-1}$, or about 13%, comes from mobile AC (Fig. 3). The reduction in 2015–2050 cumulative emissions is about $0.8 \text{ GtCO}_2\text{-eq}$. The estimated reductions also depend somewhat on the assumptions made in the implementation of the regulations (see SM).

Concerning HFC RF, the EU regulations lead to a reduction of $5.9\text{--}7.2 \text{ mW m}^{-2}$ (about 53%) by 2050, while the enacted regulations in the USA and Japan reduce the RF by $11.6\text{--}13.8 \text{ mW m}^{-2}$ (about 37%) and $1.5\text{--}1.7 \text{ mW m}^{-2}$ (about 29%), respectively, by 2050 (Fig. S8). The percentage reductions in RF are not as large as in emissions because of the long atmospheric lifetimes (5–50 years) of the major high-GWP HFCs.

The success of EU, USA and Japan regulations likely will require changes in sector technologies that currently use high-GWP HFCs. Furthermore, the availability of new technologies is likely to cause some reductions in the use of high-GWP HFCs in other countries, thereby increasing the climate benefits of these national regulations. If global adoption of these technology changes is assumed, the response of the baseline scenario is a reduction in emissions from $4.0\text{--}5.3$ to $1.5\text{--}1.9 \text{ GtCO}_2\text{-eq yr}^{-1}$ by 2050 (Fig. 4B). Cumulative emissions are reduced by $38\text{--}46 \text{ GtCO}_2\text{-eq}$, from $91\text{--}105$ to $53\text{--}59 \text{ GtCO}_2\text{-eq}$, over the 2015–2050 period (Tables S5 and S6). Similarly, if global adoption of the technologies required to meet the USA SNAP changes is assumed, the response is a reduction in global emissions to $1.9\text{--}2.5 \text{ GtCO}_2\text{-eq yr}^{-1}$ by 2050 and a reduction in cumulative emissions by $36\text{--}44 \text{ GtCO}_2\text{-eq}$ over 2015–2050. Similar reductions in emissions are found for the Japanese regulations: emissions reduced to $2.0\text{--}2.6 \text{ GtCO}_2\text{-eq yr}^{-1}$ by 2050 and a cumulative emissions reduction of $28\text{--}35 \text{ GtCO}_2\text{-eq}$ over 2015–2050. Thus, assuming the global adoption of any one of these national regulations reduces global HFC emissions by 50–65% by 2050.

6. Proposed Montreal Protocol amendments for HFC reductions

Several amendment proposals have been submitted to the Montreal Protocol to control global consumption and production of HFCs. In 2015, proposals were submitted by North America

(Canada, Mexico and the USA) (UNEP, 2015b), Island States in the Pacific (UNEP, 2015e), the EU (UNEP, 2015c), and India (UNEP, 2015d). In each proposal HFC annual production and consumption in developed and developing countries are reduced on phasedown schedules relative to specified base levels. Since the phasedown schedules are not fully specified for developing countries in the EU and India proposals, some intermediate reduction steps are assumed in the present analysis (Table S7).

Differing base levels across regions directly affect the global emission reductions that result from implementing a proposal because reductions in the baseline scenario begin at those values. For developed countries, the base levels are determined primarily by the historical HFC use, while for developing countries it is a combination of both HFC and HCFC use (Table S8). The country/region phasedown (in $\text{CO}_2\text{-eq}$) in HFC consumption (and production) in each proposal can be achieved with a wide range of strategies. The strategy assumed in this analysis is to reduce high-GWP HFC use equally in all sectors following the specified phasedown schedule for each region and to replace that use with low-GWP alternatives resulting in a lower overall GWP for each sector. Other strategies following the same consumption phasedown, but first targeting certain HFCs, such as HFC-143a, that have longer atmospheric lifetimes than the most used HFCs, might result in a somewhat different RF in 2050 compared with reducing all HFCs simultaneously.

The potential reduction in HFC consumption, emissions, and RF resulting from the Montreal Protocol proposals are shown in part in Fig. 5 and Figs S9 and S10. In the EU proposal there are different controls for HFC production and consumption in developing countries. The corresponding curves of both are shown, since due to the uncertainty in future import and export levels, it is not clear which one will be more limiting for future consumption and emissions in a specific country/region. The EU proposal mentions that intermediate reductions steps are to be determined by 2020 for both production and consumption in developing countries. Global consumption in the baseline scenarios is reduced by 90% or more by 2050 by implementing each of the proposals, except for one. For developed countries, the proposals yield similar reductions in consumption and emissions. The range in reductions is larger for developing countries because, for example, controls only start in

2031 in the India proposal after developing country/region consumption exceeds that from developed countries. Implementing the North America proposal reduces total cumulative emissions by 60–75 GtCO₂-eq, from 91–105 to about 31 GtCO₂-eq, over the 2015–2050 period (Table S10), with similar reductions from the Pacific Island States and EU proposals (production controls). The reduction in cumulative emissions is less for the India proposal (25–36 GtCO₂-eq over 2015–2050) because of the later start of the controls for developing countries than in the other proposals.

The national regulations evaluated in Fig. 3 are expected to be met by using a combination of existing and new technologies and substances. Consequently, it is of interest to examine the reductions in the baseline scenario from regional or global implementation of these national proposals. In each case the reductions are referenced to the cumulative reduction in consumption or emissions from implementing the North America Montreal Protocol proposal. Fig. 6 (or Fig. S11 for emissions) shows that in most cases the reduction in consumption is more than 50% of the North America reference value. Also of interest is a comparison of the cumulative reductions from the global implementation of national regulations with that for the North America proposal. For global consumption in 2050 (Fig. 6, Table S9), the reductions are about 64% for the EU regulations, about 55% for the USA SNAP list, and about 50% for the Japanese regulations. Similar results are found for cumulative emissions (Fig. S11, Table S10). When comparing the national regulations with other Montreal Protocol proposals, similar reductions are calculated except for the India proposal. The reductions in consumption calculated for the India proposal are about the same as calculated for the global effect of the national regulations.

Reductions in cumulative HFC consumption

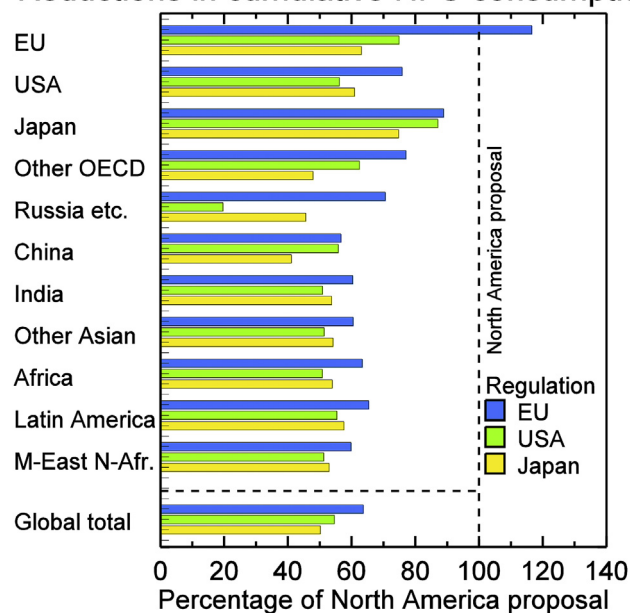


Fig. 6. Projected regional and global reductions in cumulative HFC consumption in the baseline scenario relative to that projected by implementing the North America proposal to amend the Montreal Protocol (97–125 GtCO₂-eq (2015–2050)) (see Fig. S9). The regional reductions are those that result from implementing the EU, USA or Japanese national regulations in that region, with a five-year delay for developing countries (compare Fig. 3). A reduction of 100% means that the regional reduction in consumption is equal in magnitude to the regional reduction from the phasedown of the North America proposal. The EU regulations include the directive and bans of the EU F-gas regulation. The phasedown schedule of the F-gas regulation is only implemented in the EU since the base level is defined specifically for the EU. The underlying consumption data are presented in Tables S5 and S9. See Table S10 and Fig. S11 for the corresponding reductions in cumulative emissions. Regions are defined in Fig. 1.

National regulations are sufficient for most countries to reduce 2050 HFC consumption or emissions to about 50% of the estimated reductions from full implementation of the amendment proposals. Achieving the remaining 50% requires overcoming additional technical challenges and challenges to enhancing or expanding the national regulations.

The EU regulations, though, are sufficient to reduce EU consumption and emissions in accordance with the phasedown of the North American proposal (Fig. 6 and Fig. S11). However, estimated reductions in the USA from motor vehicle emissions credits and from listing HFCs as unacceptable in specific uses under SNAP achieve only about 55% of the reduction necessary to meet the proposed Montreal Protocol phasedown proposal. This arises in part, because the SNAP actions do not yet restrict HFC use in stationary AC.

Differences in emission reductions in the Montreal Protocol scenarios translate into related differences in the estimated reductions in HFC RF. In the baseline scenario HFC RF reaches 0.22–0.25 W m⁻² in 2050 and continues to increase afterwards, while it peaks before 2040 at 0.06–0.07 W m⁻² after implementing the North America, EU or Pacific Island States proposal. Implementing the India proposal causes the HFC RF to peak around 2050 at about 0.15 W m⁻².

7. Alternatives for high-GWP HFCs and energy efficiency

Alternatives for high-GWP HFCs are already commercially available for several sectors, notably mobile AC and commercial and industrial refrigeration, and are under development for others (see Table S3, (UNEP, 2011, 2014)). The direct CO₂-eq emissions of high-GWP HFCs and alternative substances are only one aspect in estimating the total climate impact of an application. Also important are indirect CO₂-eq emissions from the fuels used to power the equipment, the energy saved by using insulating foams, and the embodied CO₂ emissions of each application from its production, service, and recycling at the end of product life. Other analyses have calculated life-cycle climate performance (LCCP) including direct, indirect, and embodied emissions on specific products but have not yet aggregated those bottom-up estimates in a global framework (IPCC/TEAP, 2005; Pappasavva et al., 2010).

HFC refrigerant emissions contribute almost all of an application's carbon life-cycle footprint when electricity is supplied from low-carbon sources such as hydroelectric, nuclear, wind, and solar, but HFC emissions account for only about 10% or less of the footprint in leak-tight systems with electricity is supplied from high-carbon sources such as coal (IPCC/TEAP, 2005). The implication is that, when both direct and indirect climate forcings are considered in baseline scenarios, improvements in energy efficiency and any transition to low-carbon energy sources could help reduce the net CO₂-eq emissions associated with future HFC use (Davis and Gertler, 2015; Phadke et al., 2014) and could even offset increases in the GWP of the HFC used in certain circumstances. Conversely, if a lower-GWP HFC is used that leads to reduced energy efficiency, it is possible that the total CO₂-equivalent emissions associated with that application could increase. Thus, to obtain a complete picture, both direct and indirect CO₂-equivalent emissions need to be considered.

As an example, we calculated the direct and indirect CO₂-eq emissions from domestic stationary AC systems for India. In a business-as-usual scenario there are about 116 million domestic AC units in India in 2030, each using about 2100 kWh yr⁻¹ and requiring 143 GW of peak power generation (Phadke et al., 2014). The associated CO₂ emissions depend on how the electricity is generated. For different types of fossil fuel combustion the estimate is 1.1–2.0 tCO₂ yr⁻¹ per AC unit (US-EIA, 2015). The CO₂-eq

emissions from the refrigerant depend on its annual emissions and GWP. For R-410A, a commonly used refrigerant blend of HFC-32 and HFC-125 with a GWP of 2077, an estimated annual emission of 50–100 g yr⁻¹ per AC unit (from (SKM, 2012) and Table S1) corresponds to 0.1–0.2 tCO₂-eq yr⁻¹. Thus, in this case the refrigerant represents only about 10% of the annual climate forcing contribution (100-yr basis). Using instead of R-410A a refrigerant with a GWP of about 700 (such as HFC-32 or HFO/HFC blends) gives the same reduction in CO₂-eq emissions on average as a 6.5% improvement in energy efficiency. Using a refrigerant with a GWP of 10 or eliminating emissions of the higher GWP refrigerant has the same CO₂-eq reduction on average as a 9.2% improvement in energy efficiency. For comparison, a 9.2% energy savings in 2030 translates into a reduction in peak energy demand of 13.2 GW or, equivalently, the construction of about 25 fewer 500 MW power plants in India (see also (Phadke et al., 2014)).

8. Conclusion

In new business-as-usual projections the use and emissions of HFCs grow steadily in coming decades. By 2050, HFC emissions contribute significantly to global climate forcing in our baseline scenarios; HFC CO₂-eq emissions represent 6–9% of global CO₂ emissions in 2050, which corresponds to 12–24% of the increase from business-as-usual CO₂ emissions from 2015 to 2050. These new projections are the first to comprehensively assess production and consumption of individual HFCs in multiple use sectors and geographic regions with emission estimates constrained by atmospheric observations. The objective of several existing national, regional and global regulations is to limit growth in future HFC use and emissions. The scenario projections allow us to estimate the impact of proposed amendments to the Montreal Protocol and existing national and regional regulations by region and sector on reducing the long-term climate forcing contribution of HFCs.

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Appendix A. Supplementary material

Supplementary material related to this article can be found at <http://dx.doi.org/10.1016/j.atmosenv.2015.10.071>.

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