The implications of residential air conditioning refrigerant choice on future hydrofluorocarbon consumption in the United States

David S. Godwin\textsuperscript{a} and Rebecca Ferenchiak\textsuperscript{b}

\textsuperscript{a}United States Environmental Protection Agency, Stratospheric Protection Division, Washington, DC, USA; \textsuperscript{b}ICF, Greenhouse Gas Mitigation and Sustainability, Washington, DC, USA

ABSTRACT

As the primary alternative to ozone-depleting refrigerants, hydrofluorocarbons (HFCs) have increased in use and emissions in the United States. This increase, and a large portion of total U.S. HFC consumption, is expected due to the use of HFCs in residential air conditioning (RAC). The RAC market primarily relied upon chlorodifluoromethane, a hydrochlorofluorocarbon (HCFC) known as HCFC-22, whose consumption is being phased out globally under the Montreal Protocol on Substances that Deplete the Ozone Layer and under national regulations such as the Clean Air Act in the United States. The RAC market today relies on HFCs, most often R-410A (a blend of difluoromethane or HFC-32, and pentafluoroethane or HFC-125) for new equipment, but older units using HCFC-22 remain. The RAC industry is investigating multiple alternatives with global warming potentials (GWPs) significantly below that of R-410A. Research has been conducted by chemical producers, air conditioner and component manufacturers, national government laboratories, academia, and consortium efforts. Various low-GWP alternatives have been suggested with GWPs of approximately 750 and below. This paper investigates industry-wide HFC reduction measures in the United States across sectors that have transitioned from ozone-depleting substances to HFCs. Under various scenarios with RAC refrigerants with GWPs in the 150-750 range, this paper shows that future RAC refrigerants will strongly influence industry efforts to reduce U.S. HFC consumption. These reductions are not just reliant on manufacturers introducing new equipment with low-GWP alternatives. The service industries, responsible for repairing leaks and recovering refrigerant, play a vital role in reducing HFC consumption.

ARTICLE HISTORY
Received 13 September 2019
Accepted 14 April 2020

KEYWORDS
HFC consumption; global warming potential; hydrofluorocarbon; ozone-depleting substance; refrigerants; residential air conditioning

CONTACT
Rebecca Ferenchiak \textsuperscript{b} Rebecca.Ferenchiak@icf.com ICF, Washington, DC, USA

This is a work of the U.S. Government and is not subject to copyright protection in the United States. The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency. It has been subjected to review by the Stratospheric Protection Division and approved for publication. Approval does not signify that the contents reflect the views of the Agency.
This article was originally published with errors, which have now been corrected in the online version. Please see Correction 10.1080/1943815X.2020.1803597

© 2020 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
1. Introduction

The use of hydrofluorocarbons (HFCs) has allowed the rapid phaseout of ozone-depleting substances (ODS) – including halons, chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) – in applications for which other alternatives were not readily available. HFCs have replaced a significant portion of past and current demand for ODS in refrigeration and air-conditioning, insulating foams, propellants used in metered dose inhalers and technical aerosols, specialized fire protection equipment, and in other applications. With the increasing global uptake of such technologies, especially refrigeration and air conditioning, HFC use and emissions are expected to increase significantly (UNEP, 2019).

As potent greenhouse gases, the emissions of HFCs have raised concerns over their impact on the global climate. These concerns have led to continued pressure to reduce their consumption and emissions, with various national, regional and international controls considered and, in some cases, adopted. There is no federal policy in the U.S. to reduce use and emissions of HFCs across all the sectors in which they are utilized; however, some U.S. states have implemented or are studying the implementation of programs to control HFC use (e.g. CARB 2019). Global reduction of the use of HFCs could lead to the avoidance of as much as 0.2 to 0.4 degrees Celsius temperature increase by 2100 (WMO, 2019).

Many options for reducing emissions of HFCs have been enumerated and studied (Schaefer et al. 2005; de la Chesnaye and Weyant 2006; Godwin et al. 2010; U.S. EPA 2013; Ragnauth et al. 2019). Equipment manufacturers are redesigning products that replace HFCs with a lower GWP substance or not-in-kind technology or that reduce the amount of HFCs needed for a specific application. Other options involve reducing leaks and implementing responsible handling practices during manufacture, installation, operation and disposal. Good refrigerant management and proper handling can help reduce the need for consumption of virgin refrigerant, for example from the full recovery and re-use of the refrigerant and/or sending supplies to reclaimers who will then ensure refrigerant meets purity requirements before selling it to the market.

Often, these changes can also improve energy efficiency, reducing associated carbon dioxide (CO₂) emissions and other air pollutants. Some of these options (reducing leaks and improving handling) can be implemented immediately for quick emission and consumption reductions, provided the service, distribution, and reclaimer industries cooperate in implementing such options. However, because many of the types of equipment that rely on these gases, in particular air conditioning and refrigeration equipment and fire suppression systems, have lifetimes ranging from 5 to 40 years, fully implementing some of these other options can take decades, assuming there is no premature retirement or retrofitting of the previous equipment, even if equipment manufacturers introduce new models and stop offering models using high-GWP HFCs. These options would, however, see an immediate reduction in HFC consumption (i.e. when the new equipment is introduced), although consumption for servicing the former HFC-based equipment could still be required.

Previous work has pointed out the importance of introducing an alternative compound for new unitary air conditioning towards reducing U.S. consumption of HFCs (Godwin et al. 2010). R-410A (a blend of HFC-32 and HFC-125), the primary refrigerant used in these applications, has a GWP of 2,087.5. More recently, multiple alternative refrigerants have
been proposed for this application (AHRI, 2018; UNEP 2019). A group of air conditioning equipment manufacturers, HFC producers, and industry and environmental organizations has asked the State of California to phase out the use of HFCs with a GWP greater than 750 in this equipment, starting in 2023 (AHRI et al., 2018).

This paper examines the effect on HFC consumption of a similar replacement of HFCs with different alternatives with GWPs not exceeding 750 in residential unitary air conditioning equipment if applied to the entire United States. This paper also explores the potential influence on these results based on the cooperation of the service, distribution, and reclamer industry. Although this paper does not analyse a particular reduction target, scenarios are evaluated on an HFC consumption basis for consistency with how ODS and HFCs are regulated through the Montreal Protocol (i.e. on a consumption and production basis, rather than an emissions basis). ODS or HFCs that are produced are assumed to eventually leak or otherwise be emitted, either through operational, servicing, or end-of-life emissions (unless material is captured and destroyed).

2. Methodology

2.1. Baseline scenario

To estimate business-as-usual (BAU) consumption of HFCs in the United States, we rely on the Vintaging Model developed by the U.S. Environmental Protection Agency (EPA) (U.S. EPA 2019a). This peer-reviewed model provides a bottom-up estimate of the use and emissions of HFCs in the United States from over 60 end-uses that are in the process of phasing out ODS or have already done so (U.S. EPA 2018a). The model allows calculations of the need for virgin HFC consumption to manufacture new products for the U.S. market and maintain existing ones over time.

Examining the baseline, we find that three major subsectors have contributed or are expected to contribute most significantly to overall HFC consumption in carbon dioxide equivalent terms. From 1992 to 2011, consumption of HFC-134a for light-duty passenger motor vehicle air conditioning (MVAC) was estimated to be the largest source of HFC consumption. This continues to be a significant source of HFC consumption globally (UNEP, 2016). Large retail food (e.g. supermarket commercial refrigeration) is the second-largest source of HFC consumption through 2011 and again from 2013 throughout the rest of the time series. Starting in 2012, and lasting at least through 2050, the residential unitary air conditioning subsector is expected to be the largest source of HFC consumption within the U.S. BAU baseline. We would expect the same globally as the uptake of air conditioning, especially in growing economies, expands (UNEP, 2016). Figure 1 depicts the estimated U.S. consumption baseline through 2050. For instance, we see that in 2012 light-duty passenger vehicle air conditioners, large retail food, and unitary air conditioning made up 18%, 17%, and 18%, respectively, of the total HFC consumption baseline of 252 million metric tons of carbon dioxide equivalent (MMTCO2eq). Remaining HFC consumption includes other refrigeration and AC end-uses (28% in 2012) such as commercial comfort cooling (i.e. chillers), stand-alone commercial refrigeration, and industrial refrigeration; foam blowing (12%); aerosols (4%); fire suppression (3%); and solvents (1%).

Under the baseline scenario, consumption of HFCs in the United States is expected to fall in the near future due to assumed transitions already occurring in the market (e.g.
HFO-1234yf in light-duty MVAC systems) and the assumption of a robust servicing industry that recovers, reclaims if needed, and reuses refrigerant from expired equipment. Nonetheless, once those transitions have fully penetrated the existing stock of equipment, and even with the assumed refrigerant recovery and reuse, HFC consumption is expected to continue increasing through 2050 and beyond, in large part due to increasing consumption in the RAC sector and as other historically ODS-consuming sectors have begun transitioning to HFC alternatives.

While recovery during routine service does not affect consumption (assuming any recovered and returned refrigerant would be replaced to maintain the equipment), recovery at disposal offsets the need for virgin refrigerant for servicing existing or manufacturing new equipment. The Vintaging Model assumes recovery rates of 15% to 95% of the refrigerant charge, which varies based on the amount of refrigerant likely remaining in equipment at time of disposal, and the recovery efficiency specific to each equipment type (influenced by the rate of compliance with refrigerant recovery laws, the technical efficiency of refrigerant recovery equipment, and the technical performance of technicians). The black line in Figure 1 depicts a hypothetical scenario in which no recovery and reuse at disposal of refrigeration and air conditioning equipment is assumed (i.e. all refrigeration and AC equipment were modelled assuming a 100% release of refrigerant remaining at end-of-life). As shown, total consumption is significantly higher. For example, consumption in 2020 is 280 MMTCO$_2$eq, 10% higher than the baseline. In 2035, the hypothetical consumption is 306 MMTCO$_2$eq, 45% higher than the baseline.

Part of the reason why the light-duty MVAC and large retail food sectors become less dominant is the refrigerant transitions that are assumed in the baseline; similar transitions are not assumed for unitary air conditioning. Within the baseline, we assume that new light-duty vehicle air conditioners transition from 1,1,1,2-tetrafluoroethane (HFC-134a)
with a GWP of 1,430 to 2,3,3,3-tetrafluoro-1-propene (HFO-1234yf) with a GWP of 4 (Papadimitriou, 2007), by 2021, based on EPA’s and the National Highway Traffic Safety Administration (NHTSA)’s 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards and EPA’s 2015 Significant New Alternatives Policy (SNAP) Rule (GPO 2012, 2015). For large retail food, some movement from R-404A (GWP of 3,921.6) to R-407A and R-407 F (GWPs of 2,107 and 1,824.5, respectively) is assumed beginning in 2001 with the full market of new systems transitioned by 2017 along with technology changes from traditional direct expansion to other technologies that use and emit lower amounts of HFCs to cool the same amount of food, in particular distributed refrigeration and secondary loops, based on EPA’s 2015 SNAP Rule and advances seen in EPA’s GreenChill Advanced Refrigeration Partnership (U.S. EPA 2018c). For example, 40% of new systems are assumed in the BAU baseline to be distributed refrigeration and 20% are assumed to be secondary loop by 2017.

Additional transitions are assumed in the baseline based on EPA’s 2015 and 2016 SNAP Rules (GPO 2015, 2016), covering many end-uses within the aerosols, foams, and refrigeration and air conditioning sectors. While these rules have been vacated in part due to litigation, EPA has not yet published a rule to respond to the partial vacatur (GPO 2018), and so no changes to the assumed baseline were made. To the extent the expected transitions were not considered to occur in the baseline, they could be assumed as mitigation options in some of the scenarios described below.

Figure 1 also depicts the vital role that the service industry plays in reducing consumption of HFCs. Even with the assumed introduction of new technologies in the MVAC and supermarket industries in the baseline, the proper recovery and reuse of refrigerant reduces consumption. Recovered HFCs are then used to service remaining stocks of equipment as models with low-GWP options are placed in operation.

### 2.2. Options to reduce U.S. consumption of HFCs

Reductions to the baseline are considered by applying within each sector several technologies or practices (“options”) to reduce HFC consumption. As described in Ragnauth et al. (2019), these options have the potential to reduce HFC emissions. For this analysis, we look at those options that also have the potential to reduce HFC consumption. It is assumed that all of these options are phased in and in place by 2021. We rely principally on reduction options identified previously by the U.S. EPA (U.S. EPA 2013, 2019b), although these have been recast to determine specifically how the options reduce consumption rather than emissions. In some cases, minor changes were made to reflect likely transitions based on recent research and announcements of new alternatives to replace high-GWP HFCs. Implementation schedules (i.e. market penetration over time) have also been revised to reflect start-up times in 2018 or later. As described below, one can develop a reduction scenario by applying some or all the options identified.

Several additional options not described in the U.S. EPA (2013) report that were included in the U.S. EPA (2019b) report have also been analysed. A full discussion of these options is beyond the scope of this paper; however, a brief summary of each is provided here:

- **CO₂ in Medium Retail Food Systems.** Carbon dioxide (R-744) has been used as a refrigerant in larger retail systems; however, here it is assumed this refrigerant
achieves wider application in the medium retail end-use (i.e. remote condensing units – often used in convenience stores and cold rooms), replacing some HFC-based equipment.

- HC-290 in Ice Makers. Propane (HC-290) is assumed to be used in lieu of HFCs for ice makers.
- R-513A in School and Tour Bus, Transit Bus, and Train AC. R-513A, a non-flammable blend of HFC-134a and HFO-1234yf, is assumed to be used in lieu of HFCs in AC systems for school and tour buses, transit buses, and trains for comfort cooling.

In addition, we consider an option where the RAC refrigerant used in new systems transitions to a lower-GWP substance, as described in section 2.4 below.

### 2.3. Mitigation scenarios

We evaluate different sets of the mitigation options to understand what additional impact the choice of the air conditioning refrigerant has on future HFC consumption.

Under Scenario 1, we look at just the option of the RAC refrigerant change and how the baseline consumption is reduced (i.e. mitigation options described in section 2.2 were not included). Although a change in refrigerant for RAC units would likely lead to the same refrigerant being used in other sub-sectors, especially unitary commercial air conditioners, in this scenario we assume the refrigerants for those other markets do not change.

In Scenario 2, the full set of mitigation options described in section 2.2 above are included with the RAC refrigerant change. This set represents an aggressive move by all the principle HFC consuming sectors – refrigeration and air-conditioning, foam blowing, aerosol propellants, solvents and fire suppression – adopting multiple options to reduce HFC consumption.

In Scenario 3, the same set of mitigation options as in Scenario 2 are revised with a view to increase the HFC consumption reduction potential. For some options, this may involve a quicker timeline until products have penetrated the market fully or to a higher saturation level. For some sub-sectors where multiple options exist, we assume more uptake of those options that have higher reduction efficiencies. In particular, for Scenario 3, we increased the market penetration of R-744 in large and medium retail food refrigeration, R-290 in ice makers, R-454B in intermodal containers for refrigerated transport, and R – 290 in residential dehumidifiers and window air conditioners (while lowering the market penetration of HFC-32), and shortened the number of years it takes to reach a maximum market penetration for a number of other options. The mitigation options assumed in Scenario 2 and Scenario 3 are described in more detail in Appendix A.

For each of the scenarios, we assume the same mitigation option in which the RAC market adopts a refrigerant in new equipment other than R-410A (GWP = 2,087.5), which is currently the baseline choice. Different GWPs are examined as explained in section 2.4 below. For simplicity, we assume an “overnight” transition so that all RAC units installed in 2024 use the new refrigerant (and all RAC units installed in 2023 use R-410A). As mentioned above, some manufacturers and others have suggested that the State of California should require a new refrigerant in all air conditioning, not just RAC, by 2023 with a six-month sell-through period. For this analysis, we extend this to 2024 (without a sell-through period) and assume it occurs for the entire United States.
2.4. **Representative RAC GWPs analysed**

We examine three different GWPs for the RAC refrigerant. All GWPs are significantly below 2,087.5, the GWP of the baseline refrigerant R-410A.

First, we examine a GWP of 750. This does not represent a specific refrigerant; however, it is a limit proposed by AHRI et al. (2018) for adoption by the State of California. To date, many refrigerants have been examined that would meet this upper limit. While most are flammable, the proposed refrigerant R-466A is not. One major air conditioning manufacturer has announced its intent to use this particular refrigerant in certain variable refrigerant flow and chiller systems for the commercial market; it remains to be seen if that use would extend to RAC or other types of air conditioners in the future (Cooling Post 2019).

We also examine a GWP of 466.3, which is the GWP of R-454B, a blend of 68.9% by weight HFC-32 and 31.1% HFO-1234yf. At least one major RAC manufacturer has announced that it will use this refrigerant in all ducted residential and light commercial air conditioning in North America (Carrier 2018). The blend is mildly flammable, with a 2 L classification under ASHRAE Standard 34 (ASHRAE, 2015), which would indicate some redesign would be needed to develop RAC equipment utilizing this refrigerant. Coincidentally, this GWP is approximately the average of the other two GWPs analysed.

For even further consumption reductions, we investigate a GWP of 150. A few known refrigerants have GWPs below this mark, including HFC-152a (GWP = 124), R-459B (GWP = 145.1), R-465A (GWP = 144.9) and R-468A (GWP = 148.1). These refrigerants are flammable and, like R-454B, would likely require some redesign to integrate these into RAC equipment. At this point, it is not known if manufacturers are pursuing these options or others with a GWP below 150 for RAC units. Such refrigerants, however, have been mentioned as part of the Global Cooling Prize, an effort to radically reduce the total climate emissions (from refrigerant and energy combined) of room air conditioners (Global Cooling Prize 2018). Any such developments could then potentially transfer to U.S.-style (unitary) RAC equipment.

3. **Results and discussion**

3.1. **Scenario 1**

Figure 2 depicts the U.S. HFC consumption from 1990 to 2050 under the baseline scenario and the mitigation Scenario 1. All GWPs analysed reduce the HFC consumption starting in 2024, the year chosen for implementation of the new RAC refrigerant. With no other mitigation options analysed, the total reduction from the RAC portion of the BAU baseline will be proportional to the GWP. In 2024, HFC consumption is reduced by 40, 48, and 58 MMTCO$_2$eq for the assumed GWPs of 750, 466.3, and 150. The resulting consumption in 2039 is 177, 167, and 157 MMTCO$_2$eq for the assumed GWPs of 750, 466.3, and 150, respectively. Using the hypothetical scenario where no recovery and reuse of refrigerant is assumed (black line), consumption is reduced by 48 MMTCO$_2$eq in 2024 for Scenario 1 with the assumed GWP of 466.3, and the consumption in 2039 is 226 MMTCO$_2$eq. Cumulative reductions from 2024 to 2050 are estimated to be 1,405, 1,621, and 1,826 MMTCO$_2$eq for the assumed GWPs of 750, 466.3, and 150, respectively, and 2,173...
MMT CO$_2$eq for Scenario 1 where no recovery and reuse of refrigerant is assumed and a GWP of 466.3.

### 3.2. Scenario 2

Figure 3 depicts the U.S. HFC consumption from 1990 to 2050 under the baseline scenario and the mitigation Scenario 2. As can be seen, HFC consumption reductions start as early

Figure 2. United States hydrofluorocarbon consumption under mitigation scenario 1, 1990 to 2050.

Figure 3. United States hydrofluorocarbon consumption under mitigation scenario 2, 1990 to 2050.
as 2018. In 2024, the RAC option begins, and the reductions begin to grow at a much faster pace at 104, 113, and 122 MMTCO$_2$e for the assumed GWPs of 750, 466.3, and 150. Even with the full set of mitigation options included, replacing the RAC refrigerant represents a good opportunity to achieve significant additional reductions. The resulting consumption in 2039 is 70, 62, and 53 MMTCO$_2$e for the assumed GWPs of 750, 466.3, and 150, respectively. Using the hypothetical scenario where no recovery and reuse of refrigerant is assumed (black line), the consumption in 2039 is 182 MMTCO$_2$e for Scenario 2 with the assumed GWP of 466.3. Cumulative reductions from 2018 to 2050 are estimated to be 4,272, 4,444, and 4,607 MMTCO$_2$e for the assumed GWPs of 750, 466.3, and 150, respectively, and 3,282 MMTCO$_2$e for Scenario 2 where no recovery and reuse of refrigerant is assumed and a GWP of 466.3.

### 3.3. Scenario 3

Figure 4 depicts the U.S. HFC consumption from 1990 to 2050 under the baseline scenario and the mitigation Scenario 3. As in Scenario 2, HFC consumption reductions begin in 2018 and deeper reductions begin in 2024, with reductions of 114, 122, and 131 MMTCO$_2$e for the assumed GWPs of 750, 466.3, and 150. Given the more aggressive mitigation options selected for Scenario 3, the RAC refrigerant options reflect less of a reduction in terms of the percentage of all options combined. Nonetheless, the RAC option still achieves significant reductions resulting in 2039 consumption of 57, 49, and 40 MMTCO$_2$e for the assumed GWPs of 750, 466.3, and 150, respectively. Using the hypothetical scenario where no recovery and reuse of refrigerant is assumed (black line), the consumption in 2039 is 164 MMTCO$_2$e for Scenario 3 with the assumed GWP of 466.3. Cumulative reductions from 2018 to 2050 are estimated to be 4,667, 4,839, and 5,002 MMTCO$_2$e for the assumed GWPs of 750, 466.3, and 150, respectively, and 3,679

![Figure 4](image_url)

**Figure 4.** United States hydrofluorocarbon consumption under mitigation scenario 3, 1990 to 2050.
MMTCO$_2$eq for Scenario 3 where no recovery and reuse of refrigerant is assumed and a GWP of 466.3.

3.4. Discussion

Under all scenarios analysed, we find significant HFC consumption reductions are achievable when including a change in the refrigerant used in RAC units. Applying other options, in an aggressive (Scenario 2) or very aggressive (Scenario 3) manner, achieves significant HFC consumption reductions by themselves. Adding the RAC refrigerant option, however, has the potential to increase total reductions in the 2035 to 2050 timeframe by roughly 50%. In all cases, the continued – and increased – recovery and reuse of refrigerant as equipment reaches disposal is critical in reducing overall consumption.

Under Scenario 1, HFC consumption in the United States is reduced by 37%, 41%, and 44% for the assumed GWPs of 750, 466.3, and 150, respectively in 2030 – just six years after the assumed overnight transition – compared to 2013. The addition of other options in Scenario 2 and Scenario 3 offer significantly higher HFC consumption reduction potential. Without assumed recovery and reuse of refrigerant under Scenario 1, HFC consumption in the United States is reduced by 15% for the assumed GWP of 466.3 in 2030 compared to 2013.

Furthermore, although scenarios are evaluated on an HFC consumption basis for consistency with how ODS and HFCs are regulated through the Montreal Protocol, reductions in HFC consumption will have an associated reduction on HFC emissions. Under Scenario 1, HFC emissions in the United States are reduced by 30%, 27%, and 25% for the assumed GWPs of 750, 466.3, and 150, respectively in 2030 compared to 2013.

Alternatively, assuming a longer manufacturing conversion time for RAC refrigerant conversion reduces the short-term HFC reduction potential. Under Scenario 1, if a ten-year manufacturing conversion is assumed (i.e. 2024 to 2033), HFC consumption in the United States is reduced by 29%, 32%, and 35% for the assumed GWPs of 750, 466.3, and 150, respectively in 2030 compared to 2013, which decreased reductions in 2030 by approximately 20% compared to an overnight transition.

A similar analysis by UNEP, 2016 examined the impacts of a six-year conversion period versus a twelve-year conversion period in manufacturing beginning in 2020. The six-year conversion resulted in a decrease in consumption of approximately 40% by the year 2026, and about 50% by 2030. The twelve-year manufacturing conversion period leads to a negligible reduction in consumption by 2026, and a 25% reduction by 2030 (i.e. half of the reduction seen through a six-year conversion). While this analysis is agnostic as to how and why a certain transition occurs, it becomes clear that the policies put forth and/or manufacturers’ actions to achieve a rapid turn-over to a new refrigerant can have a significant effect on the industry’s efforts to reduce HFC consumption.

4. Conclusions

Under a baseline (BAU) scenario, HFC consumption$^{12}$ is expected to continue increasing through 2050 and beyond, in large part due to increasing consumption in the RAC sector and as other historically ODS-consuming sectors have begun transitioning to HFC
alternatives. The RAC sector offers a significant opportunity for reductions in HFC consumption for the United States.

Furthermore, the RAC sector is a significant source of HFC consumption globally and is expected to continue to grow, particularly as countries continue to transition away from ODS and as developing countries increase use of air conditioning (UNEP 2019). The refrigerant choice adopted by the United States RAC industry could influence the transition in other countries and contribute to global HFC reduction efforts.

Although it is unclear which alternative(s), if any, industry will identify and/or choose to implement for the RAC sector, the transition to refrigerants with GWPs in the 150–750 range can provide significant reduction in HFC consumption in the United States, up to 45, 54, and 65 MMTCO$_2$eq in 2039 for the assumed GWPs of 750, 466.3, and 150, respectively, compared to a baseline of 222 MMTCO$_2$eq.

When implemented in tandem with mitigation options across the refrigeration and air-conditioning, foam blowing, aerosol propellants, solvents and fire suppression sectors, total reductions of up to 152, 160, and 169 MMTCO$_2$eq in 2039 can be achieved if the refrigerant choice in RAC meets the assumed GWPs of 750, 466.3, and 150, respectively. Additional acceleration of the timeline of implementation and/or the market penetration of alternatives can further increase HFC consumption reduction potential up to 165, 173, and 182 MMTCO$_2$eq in 2039. Alternatively, longer manufacturing conversion times could reduce or delay HFC consumption reduction potential.

These reductions are not just reliant on manufacturers introducing new equipment with low-GWP alternatives. The service industries, responsible for repairing leaks and recovering refrigerant, play a vital role in reducing HFC consumption. Without the active participation of the service industry, recovering refrigerant for reuse, much lower reductions of HFC consumption would be realized.

Although this paper is agnostic on what level of HFC consumption reductions is desired, the reader may choose a specific goal and find the scenarios and RAC GWP needed to achieve that goal. For example, the reader may choose to evaluate a goal to reduce HFC consumption by 40% in 2024 relative to an average baseline from 2011 to 2013. Under Scenario 1, HFC consumption in the United States is reduced by 15%, 19%, and 22% for the assumed GWPs of 750, 466.3, and 150, respectively in 2024 compared to 2013. The reader would therefore need to consider not only the choice of RAC GWP, but also the assumed implementation of other HFC-reduction options in other end-uses and sectors.

Notes

1. For example, Velders et al. (2015) indicated global HFC emissions could lead to a significant increase in climate forcing and contribution to climate change.
2. Under EPA’s and the National Highway Traffic Safety Administration (NHTSA)’s 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards, vehicle manufacturers have the opportunity to generate CO$_2$-equivalent credits to use in complying with the CO$_2$ standards by reducing refrigerant leakage and through the use of alternative refrigerants with lower global warming potential than the currently used HFC refrigerant.
3. The effect on the emissions of carbon dioxide and other GHGs due to energy efficiency changes is beyond the scope of this paper.
4. Consumption is defined as production (exclusive of production for transformation) plus import minus export minus destruction.

5. GWPs used in this paper are based on a 100-year integrated time horizon and are from IPCC (2007), Papadimitriou (2007), and Søndergaard (2007).

6. The Vintaging Model synthesizes data from a variety of sources, including data from EPA’s ODS Tracking System, the Greenhouse Gas Reporting Program, information from submissions to EPA under the Significant New Alternatives Policy (SNAP) program, and published sources such as documents prepared by the Montreal Protocol’s Technology and Economic Assessment Panel. EPA also coordinates extensively with trade associations and individual companies. The Vintaging Model is regularly updated to incorporate up-to-date market information, including equipment stock estimates, leak rates, and sector transitions. For additional description of the Vintaging Model, see U.S. EPA (2019a).

7. As a comparison to the modelled consumption, total net supply of saturated HFCs (except HFC-23) in bulk and in pre-charged equipment and closed cell foams reported under EPA’s Greenhouse Gas Reporting Program was 245 MMTCO$_2$eq. in 2012 (U.S. EPA 2018b).

8. While most options will reduce both consumption and emissions, albeit with possible temporal differences, some do not. For example, emission reduction from destroying HFC-containing foam would not have any effect on the actual consumption, which may have occurred decades before.

9. R-466A is a provisional designation under Standard 34 of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). The refrigerant is a blend of 49% by weight HFC-32, 11.5% HFC-125 and 39.5% trifluoriodomethane (known as R-1311).

10. The consumption seen with the three GWPs converge around 2036 in all three scenarios due to modelling effects. Because the baseline model assumes refrigerant is reclaimed at equipment disposal, by this time, with a lowering demand for high-GWP refrigerants like R-410A, a surplus of reclaimed refrigerant develops, essentially negating (in CO$_2$-equivalent terms) the need to produce or import for any new material to manufacture new equipment and service the existing stock of operating equipment.

11. Consumption in 2039 is provided because it represents the typical RAC equipment lifetime (15 years) after the assumed 2024 transition.

12. See U.S. EPA (2019b) for a discussion of emission reductions under similar scenarios.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

AHRI, Natural Resources Defense Council, Carrier Corporation, Daikin Applied Americas, Inc., Goodman Manufacturing Company, L.P., Lennox International, Nortek Global HVAC LLC, Trane Inc., The Chemours Company, Honeywell International Inc. 2018. Letter to Mary Nichols, chair, California Air Resources Board. [accessed 2018 Sept 14].

Air-Conditioning, Heating, and Refrigeration Institute (AHRI). 2018. AHRI low-GWP alternative refrigerants evaluation program. [accessed 2019 May 16]. http://www.ahrinet.org/arep.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). 2015. Addendum t to standard 34-2013, designation and safety classification of refrigerants. 1041-2336. Atlanta (Georgia, USA). [accessed 2015 Nov 2]. https://www.ashrae.org/File%20Library/Technical%20Resources/Standards%20and%20Guidelines/Standards%20Addenda/34_2013_t_20151109.pdf.

California Air Resources Board (CARB). 2019. Stationary hydrofluorocarbon reduction measures. [accessed 2019 May 19]. https://ww2.arb.ca.gov/our-work/programs/stationary-hydrofluorocarbon-reduction-measures.
Carrier. 2018. Carrier Introduces puron advance™: the next generation refrigerant for ducted residential, light commercial products in North America. [accessed 2018 Dec 19]. https://www.carrier.com/residential/en/us/news/news-article/carrier_introduces_puron_advance_the_next_generation_refrigerant.aspx.

Cooling Post. 2019. Midea opts for honeywell’s A1 aircon refrigerant R466A. [accessed 2019 Jun 26]. https://www.coolingpost.com/world-news/midea-opts-for-honeywells-a1-aircon-refrigerant-r466a/.

de la Chesnaye F, Weyant J, eds. 2006. Multi-greenhouse gas mitigation and climate policy. The energy journal, special issue, 2006. https://web.stanford.edu/group/emf-research/news-emf.stanford.edu/publications/emf_21_multigreenhouse_gas_mitigation_and_climate_policy/index.html.

Global Cooling Prize. 2018. Cooling for all, without warming the planet. [accessed 2019 May 19]. https://globalcoolingprize.org/.

Godwin DS (U.S. EPA), Van Pelt MM (ICF International), Krasney T (ICF International). 2010. An analysis of reduction opportunities for consumption of hydrofluorocarbons and comparisons to US climate policy proposals. Journal of Integrative Environmental Sciences. 7(1):187–199. ISSN 1943-815X. [accessed 2010 Aug 18]. doi:10.1080/19438151003767491.

GPO. 2015. Protection of stratospheric ozone: change of listing status for certain substitutes under the significant new alternatives policy program. Federal Register. 80:42870–42959. [accessed 2015 Jul 20]. https://www.govinfo.gov/content/pkg/FR-2015-07-20/pdf/2015-17066.pdf.

GPO. 2016. Protection of stratospheric ozone: new listings of substitutes; changes of listing status; and reinterpretation of unacceptability for closed cell foam products under the significant new alternatives policy program; and revision of clean air act section 608 venting prohibition for propane. Federal Register. 81:86778–86895. [accessed 2016 Dec 1]. https://www.govinfo.gov/content/pkg/FR-2016-12-01/pdf/2016-25167.pdf.

GPO. 2018. Protection of stratospheric ozone: notification of guidance and a stakeholder meeting concerning the significant new alternatives policy (SNAP) program. Federal Register. 83:18431–18436. [accessed 2018 Apr 27]. https://www.govinfo.gov/content/pkg/FR-2018-04-27/pdf/2018-08310.pdf.

IPCC. 2007. Climate change 2007 - The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC. http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

Papadimitriou V, Talukdar RK, Portmann RW, Ravishankara AR, Burkholder JB. 2007. CF₃CF=CH₂ and (Z)-CF₃CF=CF=CHF: temperature dependent OH rate coefficients and global warming potentials. Physical Chemistry Chemical Physics. 9:1–13.

Ragnauth S, Creason J, Petrusa J, Beach R. 2019. Non-CO2 Greenhouse Gas Mitigation Through 2050 (paper presented at the 8th International Symposium on Non-CO2 Greenhouse Gases); June 12-14; Amsterdam, The Netherlands.

Schaefer DO, Godwin D, Delhotal C. 2005. The sensitivity of emission reductions to lead times in sectors with long-lived infrastructure: A case study focusing on air conditioning and refrigeration. Fourth International Symposium on Non-CO2 Greenhouse Gases Science, Control, Policy and Implementation; July 4- 6; Utrecht, The Netherlands.

Søndergaard R, Nielsen O, Hurley M, Wallington T, Singh R. 2007. Atmospheric chemistry of trans-CF₃ CH=CHF: kinetics of gas-phase reactions with Cl atoms, OH radicals, and O₃. Chemical Physics Letters.

U.S. EPA. 2013. Global mitigation of non-CO₂ greenhouse gases: 2010-2030. [accessed Sept 2013]. https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-mitigation-non-co2-ghgs-report-download-report.

U.S. EPA. 2018a. EPA’s vintaging model of ODS substitutes—A summary of the 2017 peer review. [accessed Sept 2018]. https://www.epa.gov/sites/production/files/2018-09/documents/epas-vintaging-model-of-ods-substitutes-peer-review-factsheet.pdf.

U.S. EPA. 2018b. Greenhouse gas reporting program (GHGRP), fluorinated greenhouse gas emissions. [accessed 2018 Oct 16]. https://www.epa.gov/ghgreporting/suppliers-industrial-ghgs-and-products-containing-ghgs.
U.S. EPA. 2018c. GreenChill partnership impact. [accessed 2018 Dec 18]. https://www.epa.gov/greenchill/greenchill-partnership-impact.

U.S. EPA. 2019a. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2017. [accessed 2019 May 14]. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2017.

U.S. EPA. 2019b. Global non-CO₂ greenhouse gas emission projections & mitigation potential: 2015-2050. [accessed Sept 2019]. https://www.epa.gov/sites/production/files/2019-09/documents/nonco2_methodology_report.pdf.

U.S. Government Printing Office (GPO). 2012. 2017 and later model year light-duty vehicle greenhouse gas emissions and corporate average fuel economy standards. Federal Register. 77:62624–63200. [accessed 2012 Oct 15]. https://www.govinfo.gov/content/pkg/FR-2012-10-15/pdf/2012-21972.pdf.

United Nations Environment Programme (UNEP). 2016. Report of the technology and economic assessment panel. Decision XXVII/4 Task Force Report. [accessed Mar 2016]. https://ozone.unep.org/sites/default/files/2019-05/TEAP%20TF%20XXVII-4%20Report%20March%202016.pdf.

United Nations Environment Programme (UNEP). 2019. Refrigeration, air conditioning and heat pumps technical options committee 2018 assessment report. [accessed Feb 2019]. https://ozone.unep.org/sites/default/files/2019-04/RTOC-assessment-report-2018_0.pdf.

Velders G, Fahey D, Daniel J, Andersen S, McFarland M. 2015. Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. Atmospheric Environment, Volume 123, Part A. [accessed 2019 May 19]. https://www.sciencedirect.com/science/article/pii/S135223101530488X.

World Meteorological Organization (WMO). 2019. Scientific assessment of ozone depletion: 2018. World Meteorological Organization Global Ozone Research and Monitoring Project – Report No. 58. https://www.esrl.noaa.gov/csd/assessments/ozone/2018/downloads/2018OzoneAssessment.pdf.
### Appendix A: Description of Mitigation Options

#### Table 1. Description of mitigation options for scenario 2 and scenario 3.

| End-Use | Alternative | Scenario 2 Transition Assumptions | Scenario 3 Transition Assumptions |
|---------|-------------|-----------------------------------|-----------------------------------|
| Large Retail Food | Transcritical/Cascade CO₂ | Market Penetration (MP) 0% in 2017, rise linearly to 5% in 2019; overnight to 33% in 2020 | MP 0% in 2017, rise linearly to 5% in 2019; overnight to 75% in 2022 |
| Medium Retail Food | CO₂ | MP 0% in 2017, rise linearly to 5% in 2019; overnight to 33% in 2020 | MP 0% in 2017, rise linearly to 5% in 2019; overnight to 75% in 2022 |
| Refrigerated Transport (Trucks and Trailers) | R-452A | MP 0% in 2025, rise linearly to 50% in 2030 | MP 0% in 2020, rise linearly to 95% in 2025 |
| Ice Makers | R-290 | MP 0% in 2022, rise linearly to 50% in 2030 | MP 0% in 2022, rise linearly to 75% in 2027 |
| Window Units and Dehumidifiers | R-32 | MP 0% in 2019, rise linearly to 50% in 2030 | MP 0% in 2019, rise linearly to 25% in 2030 |
| | R-290 | Overnight transition to 50% in 2030 | Overnight transition to 75% in 2025 |
| Residential Unitary A/C | R-452B and Microchannel Heat Exchangers | MP 0% in 2025, rise linearly to 100% in 2030 | Included, no change |
| Commercial Unitary A/C | MCHE | Linear transition 0% in 2017 to 100% in 2027 | Included, no change |
| | R-32 | MP 0% in 2025, rise linearly to 100% in 2030 | MP 0% in 2025, rise linearly to 100% in 2027 |
| | R-32 and MCHE | Overnight transition to 50% in 2030 | Overnight transition to 100% in 2030 |
| PTACs and Water and Ground Source HPs | R-32/R-452B | MP 0% in 2025, rise linearly to 100% in 2030 | Included, no change |
| IPR and Cold Storage | Ammonia/CO₂ | MP 0% in 2019, rise linearly to 100% in 2025 | MP 0% in 2019, rise linearly to 100% in 2023 |
| Bus and Train AC | R-513A | MP 0% in 2024, rise linearly to 100% in 2035 | MP 0% in 2024, rise linearly to 100% in 2030 |
| MVACs and Unitary AC | Service Recovery | Beginning in 2018, reduce service emissions by 25% if the service rate is greater than 5% | Included, no change |
| Large Retail Food, IPR, Cold Storage, and Chillers | Leak Repair | Reduce leak emissions by 40%. Phase in over 2020–2025, with full market penetration | Included, no change |
| All Small End-Uses | Disposal | Reduce disposal emissions to 3% overnight in 2019. (Based on estimated 20% remaining at EOL) | Included, no change |
| All Large End-Uses | Disposal | Reduce disposal emissions to 4% overnight in 2019. (Based on 80% remaining at EOL) | Included, no change |
| PU Rigid: Spray Foam (Low-pressure, two-component) | HFC-134a to HFO-1234ze(E) | 0% in 2019, rise linearly to 30% by 2025 | Included, no change |
| Fire Suppression Flooding Agents | Inert Gas | MP 0% in 2020, rise linearly to 28.5% in 2035 | Included, no change |
| | Water Mist | MP 0% in 2020, rise linearly to 3.8% in 2035 | Included, no change |
| | 5-K-12 | MP 0% in 2017, rise linearly to 35% in 2023 | Included, no change |

(Continued)
| End-Use                              | Alternative                          | Scenario 2 Transition Assumptions                      | Scenario 3 Transition Assumptions |
|-------------------------------------|--------------------------------------|-------------------------------------------------------|-----------------------------------|
| Non-MDI Aerosols                    | HFC-134a to HC                       | Overnight transition to 20% in 2021                   | Included, no change               |
|                                    | HFC-152a to HC                       | Overnight transition to 5% in 2017, rise linearly to 10% in 2020, rise linearly to 20% in 2025 | Included, no change               |
|                                    | HFC-134a to NIK                      | Overnight transition to 20% in 2017                   | Included, no change               |
|                                    | HFC-152a to NIK                      | Overnight transition to 25% in 2017, rise linearly to 40% in 2020 | Included, no change               |
|                                    | HFC-134a to HFO-1234ze(E)            | Overnight transition to 5% in 2017, rise linearly to 20% in 2030 | Included, no change               |
|                                    | HFC-152a to HFO-1234ze(E)            | Overnight transition to 5% in 2018, rise linearly to 20% in 2030 | Included, no change               |
|                                    | HFC-134a to HFC-152a                | Overnight transition to 10% in 2021                   | Included, no change               |
|                                    | Dry Powder Inhalers (DPI)            | Overnight transition to 20% in 2020                   | Included, no change               |
|                                    | Retrofit HFC to HFE                  | Overnight transition to 60% in 2020, rise linearly to 100% in 2035 | Included, no change               |
| MDI Aerosols                        |                                       |                                                       |                                    |
| Precision Solvent Cleaning          | Retrofit HFC to HFE                  | Overnight transition to 40% in 2020, rise linearly to 80% in 2035 | Included, no change               |
| Applications                        | Retrofit Not-in-kind                 | Overnight transition to 2% in 2020, rise linearly to 10% in 2035 | Included, no change               |
|                                    | Aqueous                              |                                                       |                                    |
|                                    | Retrofit Not-in-kind Semi-aqueous    |                                                       |                                    |
| Electronic Solvent Cleaning         |                                       |                                                       |                                    |
| Applications                        |                                       |                                                       |                                    |
|                                    |                                       |                                                       |                                    |