**California Air Resources Board** **December 15, 2017**

# Potential Impact of the Kigali Amendment on California HFC Emissions

## Estimates and Methodology used to Model Potential Greenhouse Gas Emissions Reductions in California from the Global Hydrofluorocarbon (HFC) Phase-down Agreement of October 15, 2016, in Kigali, Rwanda ("Kigali Amendment").

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Written by the Research Division of the California Air Resources Board (CARB)

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## Table of Contents

## EXECUTIVE SUMMARY

To help reduce additional and preventable global warming, a global phase-down in the production and consumption of hydrofluorocarbons (HFCs) was agreed to by more than 150 nations on October 15, 2016 in Kigali, Rwanda. The intent of the phase-down is to reduce emissions of potent HFC greenhouse gases with a high global warming potential (GWP) and prevent up to 0.5 degrees Celsius of global warming by the end of this century. The global HFC phase-down agreement, commonly known as the “Kigali Amendment” or the “Kigali Agreement” became an amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer when it passed the 20-country ratification threshold on November 17, 2017. The phase-down goes into effect on January 1, 2019. Any country that ratifies it going forward will be bound by its HFC phase-down requirements. Countries that do not ratify the amendment will be subject to trade restrictions on HFCs (but not until January 2033).

The Kigali Amendment is an historic agreement which will strengthen and support California’s own goals to reduce greenhouse gases, including HFCs. Senate Bill (SB) 1383, Lara 2016, was signed into law in September 2016, and requires the reductions of HFC emissions in California 40 percent below 2013 levels by 2030. Business-as-usual (BAU) HFC emissions in California (without an HFC phase-down) are estimated to increase to 23.1 million metric tonnes of carbon dioxide equivalents ($MMTCO_2E$) annually by 2030; the 40 percent reduction below 2013 levels of 16.5 $MMTCO_2E$ requires emissions to be no greater than 9.9 $MMTCO_2E$ annually.

CARB conducted an analysis, described in this document, to determine if the global HFC phase-down schedule of the Kigali Amendment beginning 2019 was sufficient by itself to allow California to meet its SB 1383 emissions reductions goals, without additional reduction measures nationally or in California. Existing HFC reduction measures nationally and in California were considered as part of business-as-usual and were already included in projected emissions estimates.

The production and consumption schedule for developed countries, including the United States is shown below.

**Table ES-1. HFC Phase-down Schedule for Developed Countries.**

| Year | Production/Consumption Cap (relative to baseline) | Reductions in Production/Consumption |
|---|---|---|
| 2017-2018 | None | None |
| 2019 | 90% | 10% |
| 2024 | 60% | 40% |
| 2029 | 30% | 70% |
| 2034 | 20% | 80% |
| 2036 | 15% | 85% |

Using the HFC phase-down schedule and comparing to the (pre-Kigali) business-as-usual projected HFC emissions, CARB developed an emissions methodology with four different scenarios to estimate HFC emissions in California as a result of actions taken to comply with the Kigali Amendment. The reductions scenarios are listed and described below:

- H1: HFC Emissions follow Historical Reductions of chlorofluorocarbons (CFCs)
- H2: HFC Emissions follow Historical Reductions of hydrochlorofluorocarbon (HCFC)-22
- BC: "Best Case" (most rapid and greatest reductions possible)
- WC: "Worst Case" (slowest and least reductions possible)

The first two scenarios used annual emissions data of declining emissions of the ozone-depleting substances (ODS) CFCs and HCFCs that occurred when the Montreal Protocol required their phase-out. The emissions reduction rates observed for CFCs and HCFC-22, the primary HCFC, were applied to the Kigali phase-down schedule of HFCs to estimate likely HFC emissions if they follow the same trends as the previous two fluorocarbon gas phase-outs. In this methodology, historical ODS emissions reductions scenarios are labeled "H1: ODS historical reductions of CFCs", and "H2: ODS historical reductions of HCFC-22".

For the second two scenarios, CARB then bounded the emissions estimates into upper and lower reduction rates. A "best-case" reductions scenario (labeled BC) results in the fastest reductions. The scenario assumes a fast transition away from using high-GWP HFCs in refrigeration and air-conditioning (AC) equipment to lower-GWP alternatives, including the "natural refrigerants" of carbon dioxide (as refrigerant), ammonia, hydrocarbons, and the newest generation of synthetic fluorinated compounds, the hydrofluoro-olefins (HFOs). The "worst case" reductions scenario (labeled WC) results in the slowest reductions; by assuming a slow transition from high-GWP HFCs to lower-GWP alternatives.

Given the robust reduction phase-down schedule of HFCs for developed countries under the Kigali Amendment, one could expect that reduced emissions would reflect the reductions in production and consumption. However, more than 85 percent of HFCs are used in refrigeration and AC equipment. This equipment is designed to use a specific refrigerant, and average equipment lifetimes are 15 to 20 years. The result is that a high-GWP refrigerant used today in a new unit may continue emitting that high-GWP refrigerant until 2037. Considering the large installed base of millions of refrigeration and AC units already manufactured and currently in use, it takes many years for low-GWP equipment to replace the existing units. Historical data shows us that reductions of refrigerant emissions lag an average of 15 years behind equivalent reductions in production and consumption, an aspect known as "the inertia of the installed base".

The following table summarizes the scenarios used and the key assumptions used to estimate HFC emissions and reductions as a result of the Kigali phase-down.

**Table ES-2. Summary of Reductions Estimates Scenarios.**

| **Scenario Used** | **Key Assumptions Used** |
|---|---|
| H1: ODS Historical Reductions of CFCs | HFC emissions will follow the CFC emissions reductions trends as measured after the CFC phase-out. |
| H2: ODS Historical Reductions of HCFC-22 | HFC emissions will follow the HCFC-22 emissions reductions trends as measured during the HCFC-22 phase-out (to be completed January 1, 2020). |
| BC: “Best Case” | New equipment uses low and lower-GWP refrigerants as soon as technically feasible. Existing equipment using high-GWP refrigerants retrofits to lower-GWP refrigerants before HFC supply shortages occur. |
| WC: “Worst Case” | New equipment continues to use the highest average GWP refrigerant still available during the phase-down. Existing equipment uses the same high-GWP refrigerant it was designed to use, through its working life. |

The following table shows the different reductions impacts from each of the four reductions scenarios modeled. None of the phase-down reductions scenarios modeled result in reducing HFC emissions sufficiently to achieve California’s HFC emissions reductions goals by the year 2030.

**Table ES-3. Impact of the Kigali Amendment: Estimated HFC Emissions in CA in 2030 as Modeled by Four Scenarios, and Percent of Reductions Goal achieved by Each Scenario.**

| **HFC Phase-down Scenario Modeled** | **Estimated Emissions in CA 2030 ($MMTCO_2E$)** | **Percent of Emissions Goal (9.9 $MMTCO_2E$) Achieved by 2030[a] (± 15%)** | **Estimated Year Emissions Goal Achieved (± 3 Years)** |
|---|---|---|---|
| BAU: Business as Usual (no Phase-down) | 23.1 | 0% | N/A |
| H1: ODS Historical Reductions of CFCs | 16.8 | 48% | 2039 |
| H2: ODS Historical Reductions of HCFC-22 | 18.2 | 37% | 2040 |
| BC: Best Case | 14.1 | 68% | 2038 |
| WC: Worst Case | 19.2 | 30% | 2044 |

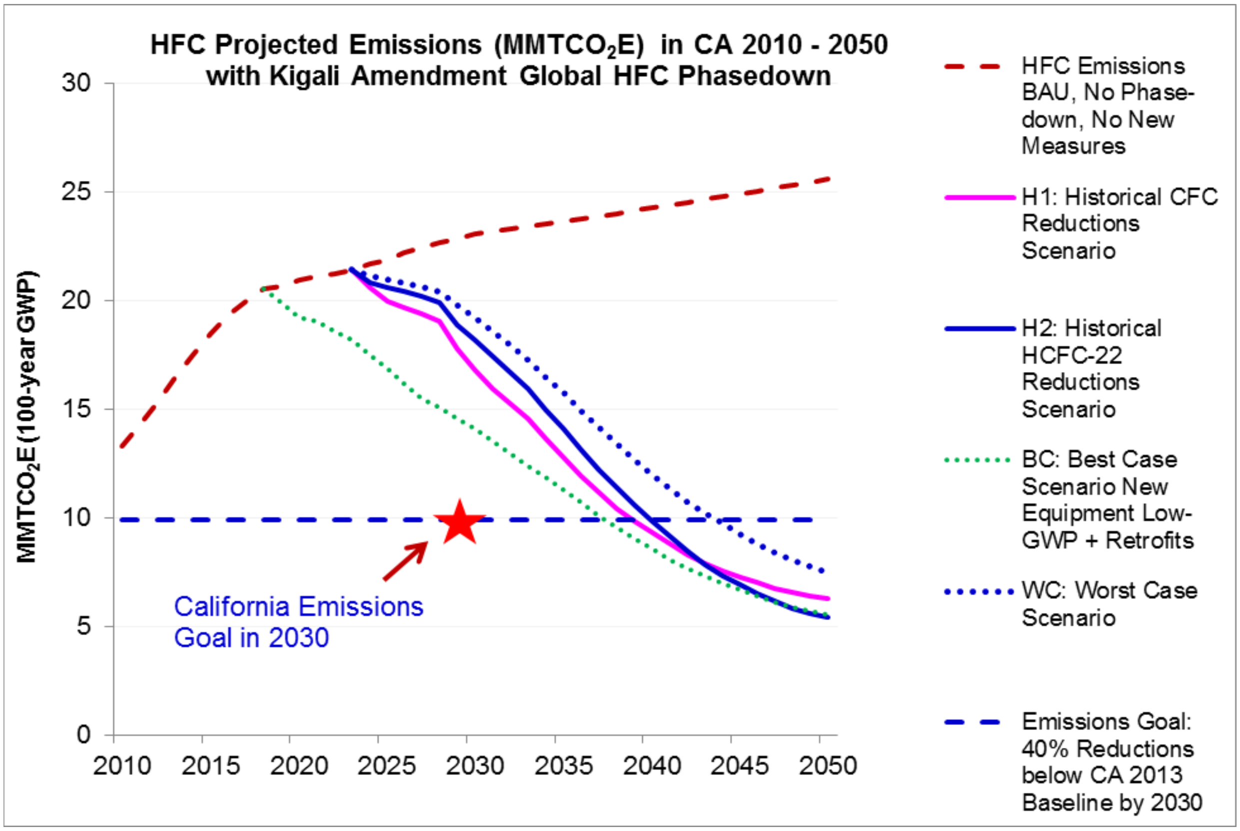
Table Notes: a) The emissions goal is to reduce annual emissions of HFCs 40 percent below 2013 levels by 2030, equal to reducing BAU emissions in 2030 of 23.1 $MMTCO_2E$ to 9.9 $MMTCO_2E$. To achieve 100 percent of the reductions goal, emissions must decrease 13.2 $MMTCO_2E$ annually below BAU.

**CARB analysis indicates that the impact of the Kigali Amendment HFC reductions on California's HFC emissions will only achieve 37 to 48 percent of total reductions required by SB 1383 by 2030, for an average of 42 percent (plus/minus 15 percent) of goal achieved. Achieving the 2030 HFC emissions reductions goal would not occur until approximately 2039-2040 (historical ODS phase-out scenarios modeled). The reductions estimate is bounded by the earliest achievable goal date of 2038 from the best-case scenario, to the latest expected goal date of 2044 from the worst-case scenario (uncertainty of plus/minus three years for all scenarios).**

**We conclude that the Kigali Amendment to reduce the production and consumption of HFCs, while strongly supported by California, will not be sufficient by itself to meet the HFC reduction goals required by SB 1383. Additional HFC reduction measures nationally or in the state of California are needed.**

Figure ES-1 below shows estimated emissions of HFCs in California through 2050 as a result of actions taken to comply with the Kigali Amendment.

**Figure ES-1. Estimated HFC Emissions in CA from the Kigali Amendment.**



## 1. PURPOSE and CONTEXT

This analysis by the California Air Resources Board (CARB) evaluates the impact of the Kigali Amendment on HFC emissions in California and compares the results with the emission reduction targets set by Senate Bill (SB) 1383 (Lara, Stats. 2016, Ch. 395) (SB 1383), "Short-lived climate pollutants: methane emissions: *dairy and livestock:* organic waste: landfills". SB 1383 requires a 40 percent reduction in California's HFC emissions below 2013 levels by the year 2030.

The context of this analysis includes determining the HFC supply baseline and subsequent phase-down steps specified in the Kigali Amendment; the national U.S. Environmental Protection Agency (EPA) regulations; and the unique California context which includes both California-specific regulations and a California-specific F-gas inventory. This context, absent the effect of the Kigali Amendment, is treated as business-as-usual (BAU) for modeling purposes.

In this methodology, BAU refers to the estimated HFC emissions with current CARB regulations in place, and with U.S. EPA Significant New Alternatives Policy (SNAP) Program Rules (as of January 1, 2017) in place (prohibiting certain HFCs from use in new equipment and materials). The BAU does not include the estimated reductions from measures that may be taken to achieve the HFC reduction goals of SB 1383, and does not include reductions from the HFC phase-down schedule as outlined in the Kigali Amendment. Appendix A describes the basics of the methodology used to estimate current and projected F-gas emissions under BAU. HFC reductions as a result of the Kigali Amendment are subtracted from BAU emissions to derive lower, post-Kigali HFC emissions.

## 2. BACKGROUND

The annual Montreal Protocol Meeting of Parties in October 2016 in Kigali, Rwanda, resulted in an historic international agreement, known as the "Kigali Amendment", to phase down the production and consumption of hydrofluorocarbons (HFCs) globally. For developed countries, including the United States (U.S.), the agreement requires specific limits on the production and consumption of HFCs starting in 2019.

The Kigali Amendment is the result of many years of international negotiations to reach a consensus on how to best reduce emissions of HFCs, synthetic fluorinated gases with global warming potential values (GWPs) hundreds to thousands of times greater than carbon dioxide ($CO_2$). HFCs are used in five main market sectors with the global proportion of HFC usage as follows:

- Refrigerants for refrigeration and air conditioning - 79 percent

- Foam expansion agents in insulating foam - 12 percent
- Aerosol propellant in consumer product aerosols and medical dose inhalers - 7 percent
- Fire suppressants - 2 percent
- Solvents - 0.3 percent

(Source: UNEP, 2015.)

HFCs are primarily produced for use as substitutes for ozone-depleting substances (ODS), including chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). Under the Montreal Protocol of 1987, CFCs have been phased out of new production and consumption, and HCFCs will be phased out of new production and consumption in the United States beginning January 1, 2020. Currently, HFCs comprise four percent of all GHG emissions in California, and are a small fraction of the total climate forcing globally (two percent), but they are the fastest growing source of GHG emissions in California and globally, primarily driven by the phase-out of ozone depleting substances and increased demand for refrigeration and air conditioning. If HFC emissions growth continues under business-as-usual, they would comprise 9 to 19 percent of all GHG emissions globally by 2050 (Velders, et al., 2009, and 2014).

HFCs are the most recent refrigerants to be banned or phased-out. The following brief history of refrigerants is provided as background.

1870s – 1927: Earliest refrigerants used included carbon dioxide, ammonia, sulfur dioxide, methyl chloride, ether, and hydrocarbons. Early concerns included toxicity and flammability.

1928 – 1995: The invention of chlorofluorocarbons first in the 1890s by Frederic Swarts, and later presented by Thomas Midgley and commercialized in 1928 under the trade name Freon®, led to an almost complete replacement of the originally used refrigerants, due to the safety (non-toxic, non-flammable) and efficacy of CFCs. HCFCs were also invented and widely used after the 1940s, mainly in air-conditioning. (Ammonia continues to be used in many cold storage warehouses and industrial applications.)

1970s: Research conducted by Frank Sherwood “Sherry” Rowland and Mario J. Molina hypothesize that CFCs and HCFCs are ODS that destroy the stratospheric ozone layer, allowing more damaging ultraviolet radiation to reach the surface of the earth. Growing awareness that ODS may be harmful to human health and the environment.

1985: Joe Farman, Brian Gardiner, and Jon Shanklin conduct ozone measurements and discover that a hole in the ozone layer above Antarctica existed, confirming the link between CFCs, HCFCs and ozone depletion.

1987: The Montreal Protocol on Substances that Deplete the Ozone Layer, an international treaty to protect the ozone layer by phasing down and banning ODS, was ratified and eventually signed by all members of the United Nations.

1996: Ban on all new production and consumption of CFCs in the U.S and other developed countries. CFCs are both highly ozone-depleting and have very-high GWPs. The most commonly used refrigerant, CFC-12, often referred to by its broader trade name Freon®, has an ozone-depleting potential (ODP) of one (the most ozone-depleting) and a GWP of 10900. CFCs were largely replaced by HCFC-22, with just 5.5 percent the ODP of CFC-12, and a GWP of 1810 (an 83 percent decrease from CFC-12). In motor vehicle AC and household appliances, CFC-12 was replaced by HFC-134a, with a GWP of 1430 (87 percent less than CFC-12). All HFCs are non-ODS.

2010: HCFC-22 banned in new equipment in the United States. Replaced by HFC blend R-410A in AC with a GWP of 2088 (15 percent greater GWP than HCFC-22), and replaced by HFC blend R-404A in refrigeration with a GWP of 3922 (117 percent greater GWP than HCFC-22). Phased-down production of HCFC-22 will be allowed until January 1, 2020, at which time no new production or import into the United States is allowed for HCFC-22 and other HCFCs. An exception applies primarily to HCFC-123: from January 1, 2020 until December 31, 2029, production and consumption of HCFC-123 and certain other HCFCs may be allowed for the servicing of existing refrigeration and air-conditioning equipment (the ODP of HCFC-123 is 1.2 percent that of CFC-11 and CFC-12, and its GWP is 77). Recycled HCFCs from previously existing stocks and banks can be used indefinitely.

Early 2000’s-2016: Growing awareness that the ozone-depleting problem of CFCs and HCFCs is being addressed by substituting ODS with non-ODS HFCs, but with the detrimental unintended consequence that as with most ODSs, HFCs themselves are potent greenhouse gases that will contribute to global warming.

The invention of hydrofluoro-olefins (HFOs) that are non-ODS and have a GWP < 10. HFOs are unsaturated HFCs that decompose in the atmosphere within several weeks, leading to a very low GWP. Reintroduction of some of the “natural” refrigerants used initially in the 1800s: carbon dioxide, ammonia, and hydrocarbons, with GWPs respectively of one, zero, and less than ten. These refrigerants are often described as natural to distinguish them from synthetic fluorocarbons.

2016: Kigali Amendment (to the Montreal Protocol) to phase down the production and consumption of HFCs was agreed to by more than 150 countries. As of December 2017, the Kigali Amendment has not been ratified or rejected by the U.S. Senate.

### Kigali Amendment Phase-down Schedule for the United States and other Developed Countries

The Kigali Amendment will phase down the production and consumption of HFCs between 2019 and 2036 in developed countries, and between 2024 and 2047 in developing countries. The intent is to reduce the total climate forcing of HFCs that contribute to global warming. The baseline, cap, and phase-down reductions will be based upon the total carbon-dioxide equivalents ($CO_2e$) of the HFCs.

The phase-down schedule for the production and consumption of HFCs for developed countries, including the U.S., is shown in the following table.

**Table 1. HFC Phase-down Schedule for Developed Countries.**

| Year | Production/Consumption Cap (relative to baseline) | Reductions in Production/Consumption |
|---|---|---|
| 2017-2018 | None | None |
| 2019 | 90% | 10% |
| 2024 | 60% | 40% |
| 2029 | 30% | 70% |
| 2034 | 20% | 80% |
| 2036 | 15% | 85% |

The consumption of HFCs is the annual net supply. Consumption is also defined as the production and import of HFCs into a given country, less the amount of exports and destruction. Because the Kigali Amendment applies to both production and consumption, the two terms are often used together. In this methodology, the terms “production/consumption” and “consumption” are synonymous with the available supply of new HFCs in a given time frame. If HFCs are imported into the United States and stockpiled for eventual use, the quantity, if properly reported, would be included as consumption, even if the HFCs were not used in that year or even for decades.

The production/consumption units of measure are in carbon dioxide equivalents ($CO_2$-equivalents, $CO_2$-eq, $CO_2$eq, $CO_2$e, or $CO_2$E). All HFC mass (pounds, kilograms, metric tonnes, etc.) is converted to $CO_2$-equivalents based upon its 100-year GWP value as listed in the 2007 Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007).

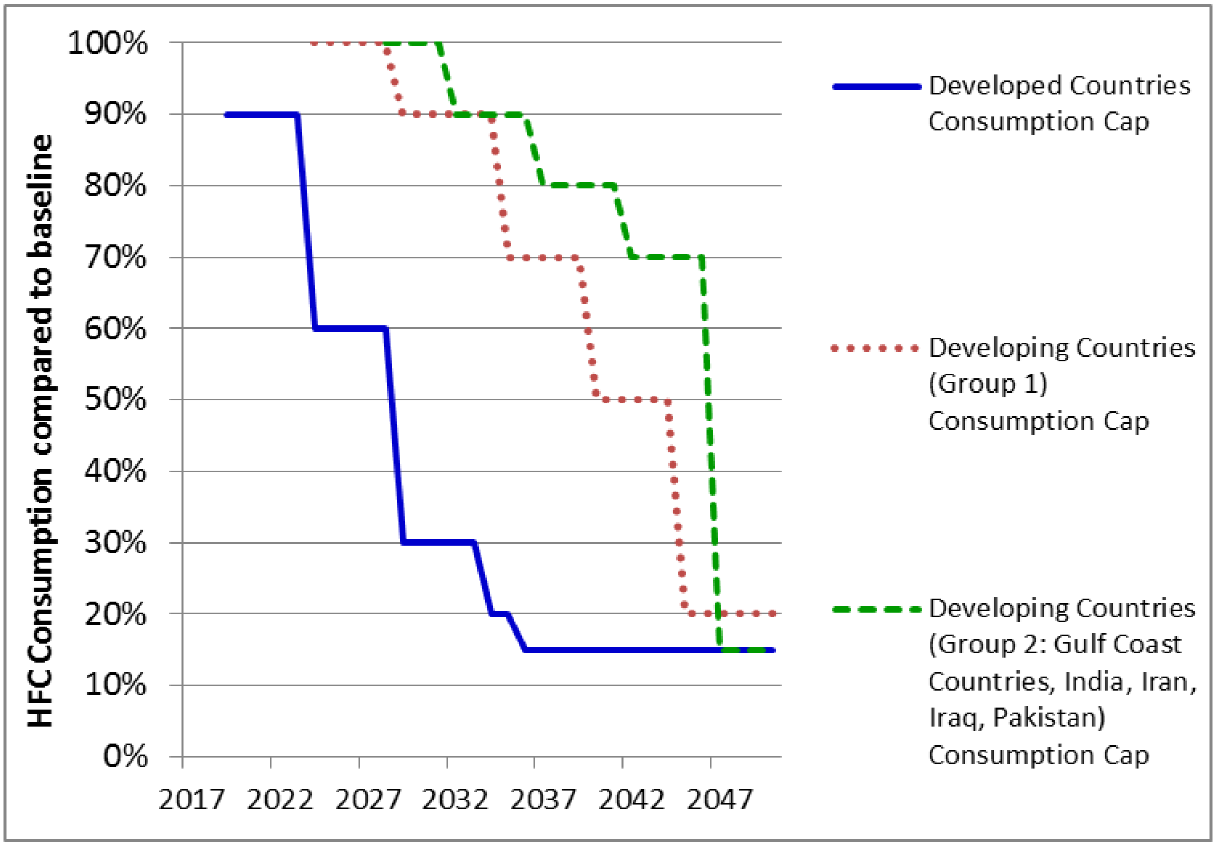
The production/consumption cap beginning in 2019 is relative to baseline production and consumption (in $CO_2$-equivalents) as follows: the average annual production and consumption of all HFCs 2011-2013, plus 15 percent of baseline production and consumption of hydrochlorofluorocarbons (HCFCs) in 1989 (the HCFC cap includes 2.8 percent of the CFC production/consumption in 1989 as agreed for the HCFC baseline). Additional discussion of the baseline is found in Appendix F, “Further Background on the Kigali Baseline”.

The phase-down schedule for developing countries is much slower and delayed compared to developed countries. For reference, the HFC phase-down schedule is shown below with a comparison between developed and developing countries.

The Developing Countries Group 1 includes all countries listed in the Montreal Protocol as “Article 5” (A5), or developing countries, with the exception of the Developing Countries in Group 2, which are the Gulf Cooperation Council Countries (Saudi Arabia, Kuwait, the United Arab Emirates, Qatar, Bahrain, and Oman), plus India, Iran, Iraq, and Pakistan.

The common element among Group 2 countries is that they all have climates with high-ambient temperatures, and these countries expressed concern over giving up HCFC or HFC refrigerants (known to be efficient in high-ambient temperatures) and replacing them with newer refrigerants they felt had not been fully proven in high-ambient temperatures. The following figure shows the HFC phase-down schedules for the three groups of countries.

**Figure 1. Global HFC Phase-down Schedule for the Three Groups of Countries**



The following table shows the phase-down schedule in tabular format.

**Table 2. Global HFC Phase-down Schedule including Developing Countries.**

| | Kigali Amendment HFC Production/Consumption Cap[1] | | |
|---|---|---|---|
| **Year** | **Developed Countries** | **Developing Countries Group 1** | **Developing Countries Group 2** |
| 2019 | 90% | Unlimited | Unlimited |
| 2024 | 60% | Freeze (100%) | |
| 2028 | | | Freeze (100%) |
| 2029 | 30% | 90% | |
| 2032 | | | 90% |
| 2034 | 20% | | |
| 2035 | | 70% | |
| 2036 | 15% | | |
| 2037 | | | 80% |
| 2040 | | 50% | |
| 2042 | | | 70% |
| 2045 | | 20%[2] | |
| 2047 | | | 15%[3] |

Table Notes:
1) The baseline used to determine the cap for developing countries is the average annual consumption of: all HFCs for the years 2020, 2021, and 2022, (Group 1) or 2024, 2025, and 2026 (Group 2) plus 65 per cent of the HCFC baseline (2009-2010) consumption. The phase-down schedule for the developing countries may not lead to any reductions of HFC emissions until 2029-2032. In addition, because the baseline is set in the future, there may be a strong incentive to over-use HFCs to set a higher baseline and ensure a strong supply of HFCs for many years. Additionally, with the rapid increase of refrigeration and air-conditioning in developing countries, HFC emissions are expected to increase significantly even with the current phase-down schedule in place. For example, under the current phase-out schedule, India is projected to increase HFC emissions from less than 2 million metric tonnes of carbon dioxide equivalents (MMTCO$_2$E) annually in 2015 to more than 40 MMTCO$_2$E annually by 2030, a 20-fold increase in 15 years (Sharma, et al., 2017). Alternately, the European Union has adopted an HFC phase-down schedule that has been in place since 2015 and is more accelerated than the Kigali Agreement (EU, 2014). However, it is beyond the scope of this methodology to estimate the global impact of the HFC phase-down.

2) Most developing countries will be allowed to use 20 percent of their baseline HFC supply indefinitely if there are no changes to the Kigali Amendment.

3) In return for additional time to reduce their HFC consumption, the developing countries in Group 2 agreed to a 15 percent baseline usage from 2047 onward (the same ultimate 15 percent baseline that developed countries will follow from 2036 onward).

## Sources of HFC Emissions in California

The following pie chart shows the percent relative weighted emissions by carbon dioxide-equivalents of HFCs in California in 2016 by end-use sector (CARB 2016a).

**Figure 2. Relative Percent of HFC Emissions by End-Use Sector (CA, 2016) of Total Estimated 19 MMTCO$_2$E HFC Emissions.**

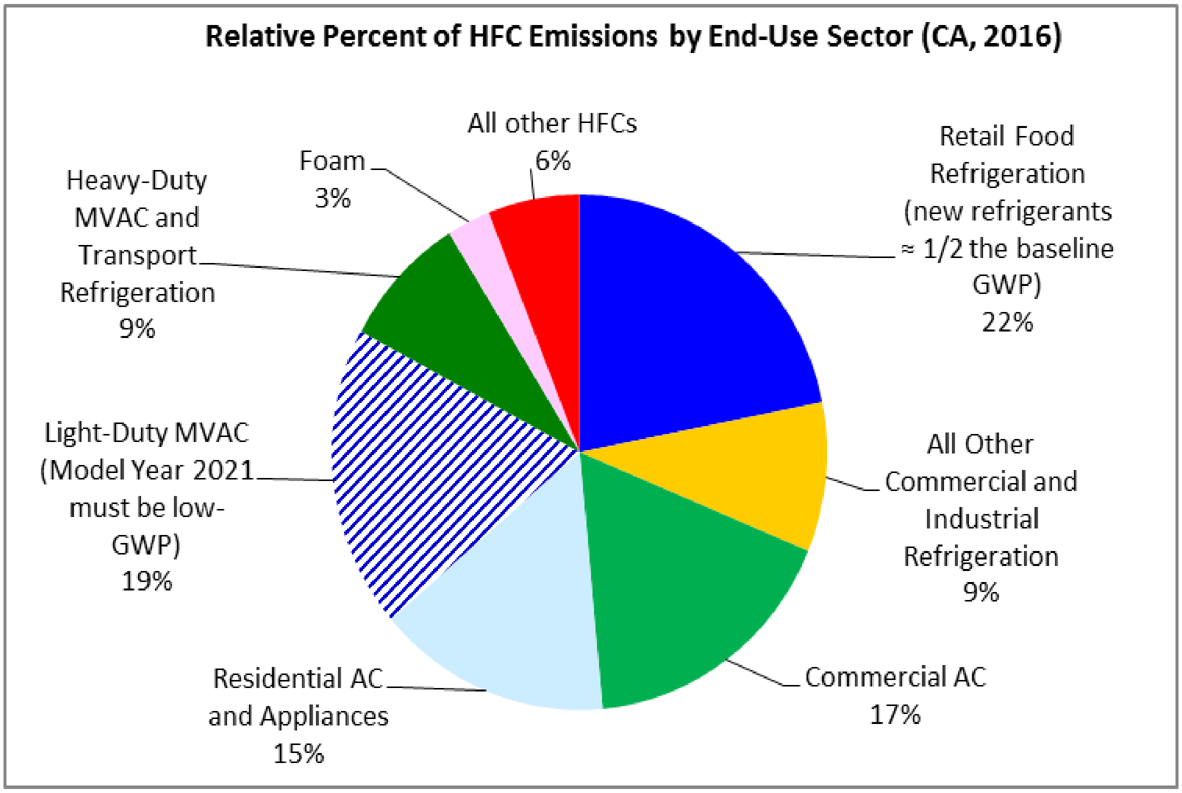


Figure Notes:
1) "All other HFCs" includes: Consumer product aerosol propellants (3.6 percent), medical dose inhaler aerosol propellants (0.8 percent), solvents (1.4 percent), and fire suppressants (0.2 percent).

Refrigerant emissions comprised approximately 90-91 percent of all HFC emissions in California in 2016. Note that refrigerant's contribution of 90-91 percent of all HFC emissions in California is higher than the 79 percent refrigerant share of global HFC usage estimated by UNEP - reasons include the long lag time between the initial use of HFCs in insulating foam and its eventual release as emissions, CARB regulations prohibiting high-GWP HFCs in aerosol propellants, and U.S. EPA SNAP regulations prohibiting many high-GWP HFCs in fire suppressants.

Retail food refrigeration emissions of HFCs are expected to decline as an overall percentage of emissions, as they begin to transition to lower-GWP refrigerants due to U.S. EPA SNAP rules. Similarly, emissions from light-duty motor vehicle AC (MVAC) will also decline due to SNAP rules. The relative share of commercial AC and residential AC will increase. In the pie chart sector for “Residential AC and Appliances”, residential AC contributes 14 percent of all HFC emissions, while refrigerator-freezers contribute one percent.

## 3. DERIVING EMISSION ESTIMATES

In this methodology all GWPs and emissions estimates are based on the 100-year GWP values as listed in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change published in 2007 (IPCC, 2007).

CARB’s F-gas Inventory is the basis of emission estimates in this methodology. The CARB F-gas Inventory profiles use of 34 distinct F-gas compounds and an additional 34 blends of F-gases, in 36 separate equipment types and emissions sectors (also called end-use sectors). A brief description of how emission estimates are derived from the F-gas Inventory is provided below and supplemental information is included in Appendix A. The full methodology is available in the GHG Inventory Technical Support Document on the CARB website at: https://www.arb.ca.gov/cc/inventory/data/data.html. The CARB F-gas Model development and relevant emissions findings are also the subjects of a paper by Gallagher, et al., 2014, published in the journal Environmental Science and Technology.

CARB’s F-gas Inventory includes eleven (11) broad categories of F-gas emission sections, which are further separated into thirty-six (36) additional subsectors (a complete list of the emissions subsectors is in Appendix A). CARB maintains an emission profile for each subsector which includes the ratio of specific F-gas compounds used or “F-gas speciation” in each vintage[1] of equipment or material, GWP values, the number of units, unit charge size, and leak rates (see Appendix A).

The historical ODS reduction scenarios H1 and H2 are modeled by applying a historical reduction curve to BAU emissions. Future emissions under BAU and the Best- and Worst-Case emission scenarios BC and WC are modeled by changing the emission profile for each subsector based on assumptions made for each scenario. The four emission scenarios and assumptions are described in detail in the subsequent section. The general approach to estimating emissions using the F-gas Inventory is described in equations one through five, below. Note that for the purposes of this methodology, the term “units” refers to a piece of equipment for stationary refrigeration and air-conditioning end-use sectors. For end-use sectors that are materials or not stationary refrigeration or AC, the following represent one unit:

- Insulating foam: One cubic meter of finished foam product.
- MVAC: One vehicle.

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[1] A vintage refers to the equipment or HFC-containing material that entered into use in a given year. In this model, the initial F-gas used at the time of production remains the substance used throughout the unit lifetime. The average annual leak rates and average end-of-life loss rates also remain fixed throughout the unit’s lifespan.

- Transport Refrigeration: One Transport Refrigeration Unit (TRU) refrigerated shipping container, ship, or train.
- Aerosol propellant: For consumer products, one can. For medical dose inhalers, one pressurized cartridge.
- One pound represents a unit for the following end-use sectors: Solvent, fire suppressant, sulfur hexafluoride, and sulfuryl fluoride pesticide.

### Equation (1) Total Annual Emissions.

$$\text{Emissions}_{\text{lbs}} = \text{Emissions}_{\text{annual op.}} + \text{Emissions}_{\text{EOL}}$$

where:

**$\text{Emissions}_{\text{lbs}}$** is the total annual emissions in pounds (lbs.).

**$\text{Emissions}_{\text{annual op.}}$** is the annual emissions from leakage occurring during unit operation as well as from servicing and maintenance (lbs.).

**$\text{Emissions}_{\text{EOL}}$** is the emissions (in lbs.) from units as they are decommissioned, recycled, or disposed of at the end-of-life (EOL).

The total pounds emitted by specific compound per year is calculated by subsector before converting to $\text{MMTCO}_2\text{E}$ (Equation 2) and aggregating across sectors for years 2010 through 2050.

### Equation (2) Conversion to $\text{MMTCO}_2\text{E}$:

$$Emissions = (Emissions_{lbs}\ X\ GWP)\ X\ (1\ MT/2{,}204.6\ lbs.)\ X\ (1\ MMTCO_2)/1{,}000{,}000\ MTCO_2)$$

where:

**Emissions** is the total F-gas emissions in million metric tonnes of $CO_2$.

**GWP** is the Global Warming Potential as published in the 2007 IPCC Fourth Assessment Report.

**MT** is a metric tonne, which is 1,000 kilograms.

### Equation (3) Annual Emissions during Operation.

$$Emissions_{annual\ op.} = Units\ X\ Refrigerant\ Charge_{EOL}\ X\ Leak\ Rate_{annual}$$

where:

**Units** are the total number of equipment or materials in use in a given year.

**Charge Size** is the average F-gas charge (lbs. per unit).

**Leak Rate** is the average annual leak or loss rate from unit operation, servicing and maintenance (expressed as a percentage of the total charge of the unit). We assume that refrigerant losses are topped off annually (re-filled to full charge size), except for the last year of equipment operation, when no top-off takes place.

### *Equation (4) End-of-Life (EOL) Emissions*

$$\mathit{Emissions}_{EOL} = \mathit{Units}_{EOL} \times \mathit{Refrigerant\ Charge}_{EOL} \times \mathit{Percent\ Loss\ of\ Charge}_{EOL}$$

where:

**Units$_{\mathbf{EOL}}$** is the number of units that have reached the final year of use/operation ("end-of-life") in which they are decommissioned or destroyed.

**Refrigerant Charge$_{\mathbf{EOL}}$** is the average F-gas charge at end-of-life (pounds per unit).

**Percent Loss of Charge$_{\mathbf{EOL}}$ L**is the average loss rate at end-of-life as the unit is decommissioned or destroyed (expressed as a percentage of the total charge of the unit).

### *Equation (5) Units in Use.*

The number of units in use in a given year is the sum of the new units that enter use in the current year, plus all the surviving equipment from previous vintage years (production years). To calculate the number of units surviving within a given vintage year:

$$Units_n = Units_{n-1} - \left[Units_{initial}\left(\frac{Current\ age}{Average\ age \times 2}\right)\right]$$

where:

**Units$_{\mathbf{n}}$** is the number units in use, within a vintage of units, in year n.

**Units$_{\mathbf{n-1}}$** is the number units in use, within a vintage of units, in the prior year.

**Units$_{\mathbf{initial}}$** is the number of units in use at the beginning of the first year of use of that vintage.

**Current Age** is the current age of the vintage in years.

**Average age** is the average age of survival for a unit in the given subsector, in years.

Equipment survival curves from several sources are used, where the number of units still operating is 100% at the time of production, 50% at the average lifetime, and 0% at two times the average lifetime. Average lifetime of a given type of equipment by definition of a survival curve means that exactly half of equipment is still operating at the time of average lifetime (Calabrese, 2004; Lawless, 2003; Weibull, 1951; and Welch and Rogers, 2010). Appendix A contains a more complete description of the equipment survival curve used in this methodology.

### Business-as-usual (BAU) Emissions

Using the emissions estimates equations and approach described above, CARB has estimated the projected BAU HFC emissions for California through 2050. In the methodology described in this document, BAU refers to the estimated HFC emissions with current CARB regulations in place, and with U.S. EPA Significant New Alternatives Policy (SNAP) Program Rules (as of January 1, 2017) in place (prohibiting certain HFCs from use in new equipment and materials). The BAU does not include the estimated reductions from the HFC phase-down schedule as outlined in the Kigali Amendment, nor does it include potential reductions from measures to meet the HFC emissions reductions goals of SB 1383.

To estimate the impacts of the Kigali Amendment HFC phase-down, we compare all estimated future emissions of HFCs with the phase-down in place, against the BAU emissions without a phase-down. The projected BAU emissions of HFCs in California are approximately ten percent lower per capita compared to the United States as a whole, because a smaller percentage of households in CA have an AC system (<70%) compared to the national average of 90% of households with AC (EIA, 2011). Additionally, HFC emissions in CA have been reduced by specific CARB regulations (consumer product aerosols, refrigerant management program, and semiconductor solvents).

### Overview of Emission Reduction Scenarios

Many methodological approaches were considered on how to best estimate emissions reductions as a result of actions taken to comply with the Kigali Amendment. The two main approaches used were applying historical emissions trends (reductions) observed in the phase-downs of ozone depleting substances (ODS) to HFC projections (Scenarios H1 and H2); and estimating both best case and worst case upper and lower bounds using California's existing emissions inventory model (BC and WC Scenarios). We note that the Kigali Amendment is a production/consumption phase-down agreement, and not an emissions reductions program. However, the long-term goal of the phase-down is to decrease specific greenhouse gas emissions to reduce their impact on global warming.

Four reduction scenarios were modeled to estimate potential HFC emissions reductions as a result of actions taken to comply with the Kigali Amendment:

- **Historical ODS Reductions Scenarios (H1 and H2)**. Historical data of ODS consumption and emissions trends associated with the global phase-down under the Montreal Protocol are applied to predict the corresponding HFC trends under the Kigali Amendment. Because the HFC phase-down has important differences from the ODS phase-down, this model includes several caveats described in the "Emissions Reductions Scenarios" section.
    - Scenario H1 uses the historical data from the CFC phase-out.
    - Scenario H2 uses the historical and projected data from the HCFC-22 phase-out.
- **Best-Case Scenario (BC)**. A hypothetical reduction scenario where all new refrigeration and AC equipment would begin using the lowest GWP refrigerants available when feasible. Refrigeration equipment using refrigerants with very-high GWPs ≥ 2500 would begin to retrofit to refrigerants with an average GWP of 1500.
- **Worst-Case Scenario (WC)**. This scenario provides the hypothetical slowest reductions case in which all existing equipment continues to use high-GWP HFCs until they retire, and new equipment uses the highest GWP HFCs still available during the phase-down. Retrofits to lower-GWP refrigerants do not occur.

Each reductions scenario is described in detail in the "Emissions Reductions Scenarios" section immediately following a description of the assumptions used to model HFC emissions reductions as a result of the Kigali HFC phase-down.

## 4. ASSUMPTIONS USED IN CARB'S KIGALI HFC PHASE-DOWN EMISSIONS REDUCTIONS MODEL

Before the different reductions scenarios are described, it is helpful to list the assumptions that are used in the HFC emissions model, its scope, and its limitations. The following assumptions are used in the methodology for estimating HFC emission reductions as a result of actions taken to comply with the Kigali Amendment. Where applicable, references and citations are included in specific document sections for a given assumption:

1. The Kigali Amendment will be adopted by the United States and its phase-down schedule will be followed as agreed upon October 15, 2016.

Caveat to assumption: The U.S. Senate must first ratify the Kigali Amendment before the United States will follow the HFC phase-down schedule. As of December 2017, the U.S. Senate had not indicated whether or not it would ratify the Kigali Amendment. Countries that do not ratify the Amendment are subject to trade restrictions on HFCs, but not until January 2033 (UNEP, 2017a).

2. All U.S. EPA Significant New Alternatives Policy (SNAP) Program changes adopted as of January 1, 2017 will be enacted as scheduled. SNAP changes include restrictions on certain high-GWP HFCs used in new production or equipment in the following sectors: light-duty motor vehicle AC, commercial refrigeration, refrigerated vending machines, small stand-alone (self-contained) refrigeration, chillers used for refrigeration or AC, household refrigerator-freezers, and insulating foam. Note that only reductions from SNAP rules above and beyond expected phase-down reductions are included in the BAU estimates. SNAP reductions were modeled first and then Kigali phase-down reductions were modeled. CARB ascertained that approximately 25 percent of SNAP reductions are “overlapping” or double-counted identical reductions that could be achieved through the phase-down by itself; these duplicated reductions are not counted twice in this methodology.

   Caveat to assumption: Due to the District of Columbia (DC) Circuit Court of Appeals decision August 8, 2017, SNAP Rule 20 was vacated. The SNAP Rule prohibited all very-high GWP refrigerants in new refrigeration equipment used in retail food, and which would lead to significant HFC emissions reductions by 2030 (if the rule is kept in place). As of this writing (December 2017), the final outcome of an appeal or further ruling was not known. However, the methodology used to estimate HFC emissions methodology is flexible enough to simply adjust the business-as-usual emissions, and the reductions from the Kigali Agreement phase-down are then applied to the new BAU emissions curve. Because additional reductions would be required to fill the absent SNAP reductions, the emissions reductions goals of California would be delayed by several more years than those shown in this document.

3. All CARB HFC emissions reductions regulations already in place as of January 1, 2017 will continue. CARB HFC regulations include: Refrigerant Management Program, small-can “DIYer” (do-it-yourselfer at-home mechanic) regulation for MVAC re-charging, semiconductor manufacturing fluorinated gas (F-gas) regulations, and consumer product aerosol propellant regulations.

4. In this emissions methodology, business as usual (BAU) emissions estimates includes all Federal and State HFC reductions measures included in assumptions 2 and 3 above. The BAU emissions estimates do not include the reductions expected from the Kigali Amendment HFC phase-downs.

5. All emissions and reductions shown in $CO_2$-equivalents (generally million metric tonnes of $CO_2$-equivalents) are based upon the 100-year GWP values as listed in the IPCC Fourth Assessment Report, 2007.

6. Average refrigerant charge sizes, annual leak rates, and end-of-life loss rates will remain constant through 2050 for the purposes of this methodology only, in order to focus results to the variables pertaining to a diminishing supply of HFCs. (In practice, CARB annually updates average refrigerant charge sizes and leak rates, and the mix of refrigerants used in equipment.) It is possible that the charge sizes, annual leak rates, and end-of-life loss rates could all decrease as a result of the global HFC phase-down; for example, due to a higher cost of high-GWP refrigerants. However, predicting the changes in these variables is beyond the scope of this methodology.

7. In the business-as-usual estimates (no HFC phase-down), all equipment uses the refrigerant it was originally designed to use; no retrofits are assumed. Retrofits are modeled in the best-case scenario, but are not included in the worst-case scenario. The historical ODS emissions reductions inherently reflect all retrofits that have occurred.

8. The actual simple weight (mass) in pounds, kilograms, or metric tonnes of compounds used as refrigerants, aerosol propellants, foam expansion agents, solvents, and fire suppressants is not expected to decrease due to the Kigali Amendment. Only the GWP value and total $CO_2$-equivalents of HFCs and HFC replacements will change due to the amendment. Refrigerant charge sizes have trended towards decreasing amounts of refrigerant used per unit of equipment since the 1990s, largely due to the increasing use of multiple distributed units instead of one large centralized system, as seen in the retail food industry. In this methodology, we keep the average charge sizes constant from baseline through 2030, as future charge sizes cannot be easily predicted.

9. The CARB F-gas emissions model developed in 2008 incorporates both initial emissions and operational emissions into the “annual leak rates” used for each specific equipment sector modeled. Initial emissions occur during installation, servicing, or retrofitting the equipment through human intervention, compared to operational emissions, which occur as leaks and losses in the absence of intervention. The model does not include GHG emissions from the production of F-gases, nor from the transportation and distribution of F-gases.

   F-gases that are blends of two or more substances are modeled first as emissions of the blend (in mass and $CO_2$-equivalents), which can then be analyzed as either emissions of the blend, or by emissions of each speciated compound (specific F-gas) within the blend. Estimated emissions results by speciated compound are compared to measured atmospheric concentrations of F-gases to help refine the bottom-up emissions model. Leakage rates of refrigerant blends assume that all refrigerant in the blend leak out at the same rate as their proportion in the blend. For example, R-410A is a blend of 50% HFC-32 and 50% HFC-125. We assume that for any given leak of R-410A refrigerant, half the emissions are from HFC-32, and half are from HFC-125. Some refrigerant blends with different boiling points are known as zeotropic, or non-azeotropic blends, which exhibit a physical characteristic known as "glide", where individual refrigerant compounds separate from the homogenous blend of all refrigerants in the blend. The separation, or glide, can lead to differential leak rates of the separate compounds within non-azeotropic blends. CARB does not model the differential leak rates of non-azeotropic blends of refrigerants.

10. HFC and HFC replacement usage is directly correlated to population. Usage as simple mass (pounds, kilograms, or metric tonnes) will increase directly with population growth, estimated by the California Department of Finance Demographics Research Unit to be 0.75% annually in California through 2050. The exception to the rate of growth of HFCs and their substitutes is for stationary air-conditioning, which is expected to grow 10 to 15 percent faster than population growth (Shah, et al., 2017), and commercial refrigeration equipment, expected to grow at 3% or more annually through 2020 (ICF, 2017). Not included in the current model, but under consideration for model improvements: a future increase in electrification of building space heating and water heating by heat pumps using refrigerants, as a result of decarbonization goals in California and other regions of the world.

11. Recovery and recycling rates of HFC blends will not increase significantly, even with a high price increase of HFC refrigerants, due to the relatively higher cost of reformulating the original HFC blends compared to simply destroying the refrigerant. Pure refrigerant compounds containing only one component are inherently easier to recycle and reclaim (than blends) because they have only one component to reclaim. Refrigerant blends must not only reclaim the refrigerant, but must duplicate the original proportions of the blend, which requires more time and energy. The American Carbon Registry estimates that currently, less than nine percent of HFCs in all end-use sectors are recovered and recycled. For pure HFC compounds such as HFC-134a used in motor vehicle AC and household refrigerator-freezers, and HFC-32, which may soon be used in large stationary AC equipment, the recycling rate could increase from the current nine percent level, although it is assumed that HFC recycling will not increase to levels sufficient for supplying replacement refrigerant to all existing equipment (the servicing demand). We further assume that re-use of refrigerants by the same business will continue or potentially increase from today's levels. For example, the HFC blend R-404A could be removed from equipment and re-used by the same business without reformulating the refrigerant to the original proportion specifications, because re-use by the same business is not considered recycling or reclamation.

12. Historical, current, and projected BAU emissions of HFCs in California have been estimated through careful analysis by CARB. The emissions estimates follow the

approach consistent with Tier 2 methodologies as described in the IPCC 2006 GHG Inventory Guidelines. The CARB methodology to estimate HFC and all F-gas emissions is based upon the U.S. EPA Vintaging Model to estimate emissions of ODS and ODS substitutes, except the CARB model uses regional input data specific to California. The methodology used has been peer-reviewed, and the results have been published in the journal Environmental Science & Technology (Gallagher, et al., 2014). An uncertainty analysis performed indicated that the uncertainty associated with HFC emissions estimates was ± 14 percent for HFC-134a; and ± 15 percent for all other HFCs. For other F-gases, the uncertainties were: ± 20 percent for CFC-12 and ± 17 percent for all other CFCs and Halons; ± 25 percent for HCFC-22 and ± 24 percent for all other HCFCs; and ± 13 percent for all other F-gases (perfluorocarbons [PFCs], perfluorocarbon/perfluorinated polyethers [PFC/PFPEs], nitrogen trifluoride [$NF_3$], sulfur hexafluoride [$SF_6$], and sulfuryl fluoride [$SO_2F_2$]).

13. The actual emissions and reductions of CFCs as reported by the U.S. EPA are an accurate historical model of a previous phase-out of a class of F-gases and the reductions curve (rate of reductions) may accurately reflect what can be expected from similar HFC phase-down steps.

14. Based upon the significant illegal importation of CFCs into the United States that occurred after the Class I ODS phase-out, it is possible that there will also be significant illegal importation of high-GWP HFCs into the United States. However, there is international discussion of increasing accuracy of harmonized tariff schedule (HTS) codes to better identify and address illegal trade. No attempt has been made to quantify future illegal imports in this methodology.

15. HCFC-22 consumption and emissions values as published by the U.S. EPA are reliable estimates of national trends of HCFC-22 use and emissions. When all new production and consumption is banned January 1, 2020, we assume continued emissions of HCFC-22 from existing equipment and recycled refrigerant, based upon the CARB emissions inventory business-as-usual projections that incorporate all F-gases.

16. In 2017 and 2018, there is no production/consumption cap on HFCs for the United States. It is likely that stockpiling could occur prior to the initial phase-down step in 2019 as it did in Europe prior to the EU F-gas regulation coming into place. However, stockpiling is not expected to be significant, in part because 1) the current supply of HFCs is very high due to past “dumping” of imported HFCs into the United States below market value (Commerce, 2016), and 2) the initial phase-down step is estimated to result in the HFC supply initially exceeding demand (CARB, 2017a).

    In February 2017, the U.S. Department of Commerce announced that HFC-134a imports were being dumped, and recommended anti-dumping duties on imports up to 167 percent. In March 2017, The United States International Trade

Commission (USITC) decided that U.S. industry was being materially injured by cheap imports of refrigerant R134a. As a result of the USITC's affirmative determination, the U.S. Department of Commerce issued an anti-dumping duty order in April 2017 (Cooling Post, 2017, DOC, 2017).

Uncertainty on stockpiling assumptions is relatively high. The American HFC Coalition contends that a significant loophole exists in the 2016 decision by the USITC to apply antidumping duties to HFC blends, but not to the individual components that make up the blends. For example, R-410A consisting of 50 percent HFC-32 and 50 percent HFC-125, is subject to antidumping duties, but the individual components if shipped by themselves, are not. The American HFC Coalition has appealed the USITC decision, stating that some companies are importing HFC components into the U.S. and blending the components into a finished HFC blend refrigerant, thus defeating the purpose of the antidumping duties (Airgas, 2016).

In the "worst case" scenario, the model estimated emissions reductions assuming significant stockpiling, and in the "best case" scenario, the model assumes negligible stockpiling. (The historical ODS reductions scenarios do not directly incorporate any stockpiling assumptions, they simply show emissions reductions as they occurred, which may have included moderate to significant stockpiling of ODS.)

17. The HFC phase-down applies to the entire United States; therefore, there will be no leakage of HFC emissions from California to other states. Most developing countries, those in Group 1, are allowed unlimited HFC production until 2024, at which time production/consumption is frozen at baseline levels; and these countries will have no required reductions in production/consumption until 2029. Group 2 countries are allowed until 2028 to freeze HFC production/consumption, and do not have to reduce HFC production/consumption until 2034 (Group 2 countries include Saudi Arabia, Kuwait, the United Arab Emirates, Qatar, Bahrain, Oman, India, Iran, Iraq, and Pakistan). Therefore, due to the very different phase-down schedules between developed and developing countries, there could be a relative abundance of HFCs in developing countries at the same time developed countries are experiencing a shortage of HFCs. One result of this inequality is that HFCs from other countries could be illegally imported into California and the United States as previously mentioned. However, illegal imports of HFCs are not specifically estimated in this methodology. Additionally, we do not attempt to estimate potential leakage of HFC emissions from California to other states if California-specific HFC reduction measures are promulgated as described in the CARB Short-Lived Climate Pollutant (SLCP) Strategy. Measures recommended in the SLCP include a sales restriction of very-high GWP HFCs with a GWP of 2500 or greater, a prohibition of new stationary refrigeration equipment containing refrigerants with a GWP of 150 or greater, and a prohibition of new stationary air-conditioning equipment containing refrigerants with a GWP of 750 or greater.

HFC reductions leakage issues as a result of California-specific HFC emissions reductions measures are more fully discussed in Appendix G: “Additionality of HFC Emissions Reductions in California and Potential Leakage of Reductions”.

18. As the high-GWP HFC supply decreases, there will be additional pressure or incentive to retrofit existing equipment, that is, remove the high-GWP HFC refrigerant and replace it a with lower-GWP alternative refrigerant. For all emissions reductions scenarios in this methodology, we assume that the recovered refrigerant is managed properly by re-using it for other equipment owned or operated by the same business, recycling/reclaiming it for re-use, or sending it to a destruction facility. However, it is possible that due to the perverse incentive of the recovered refrigerant having a negative value (costs more to recycle or destroy than it is worth), widespread intentional venting at the time of retrofit could occur, resulting in short-term emissions increases and not reductions. These potential short-term emissions due to retrofits are discussed in Appendix D, “Impact on Emissions from Servicing Demand and Retrofits”.

19. It is very unlikely that metered dose inhalers (MDIs, also known as medical dose inhalers) will stop using HFC-134a and HFC-227ea by 2036, the year of the final HFC phase-down step. This assumption is based upon the MDI sector’s continued special exemption requests from 1996 to 2012 to continue using CFCs after other emissions sectors had stopped using CFCs. In 2013, MDI manufacturers stopped using CFCs in new production and began using HFCs, after many years of reformulating research and development and at an extremely high cost. The model assumes that BAU includes continuing to use high-GWP HFCs for the MDI end-use sector.

20. The initial cost of low-GWP refrigeration and AC equipment, currently estimated to be ten percent or greater than high-GWP HFC equipment, will decrease as more low-GWP equipment is developed and produced, enjoying a larger scale of production which generally results in price decreases per unit.

21. As high-GWP HFC supplies decrease, the price will increase. Eventually, perhaps by 2029 with a 70 percent reduction in supply, the price of high-GWP HFCs will be too high to rationalize its use in any new equipment and to meet the servicing demand (replacing leaked refrigerant) in equipment still using high-GWP HFCs.

22. The price of natural refrigerants (carbon dioxide, ammonia, and hydrocarbons) will not increase or decrease as a result of the Kigali Amendment or California HFC measures. Currently, the natural refrigerants are a fraction of the cost of HFCs, in part because they cannot be patented by any one company or group of companies, and also because they are very common byproducts of other industrial processes.

23. The price of hydrofluoro-olefins (HFOs), the newest synthetic fluorinated refrigerant is currently very high, but this price is expected to decrease as HFO production increases to supply the low-GWP substitutes needed to replace HFCs.

24. The entire lifecycle cost of low-GWP equipment should not be significantly greater than traditional high-GWP HFC equipment, and should be approximately the same after maintenance, refrigerant cost, and energy cost are included in lifecycle cost. Using flammable refrigerants or slightly flammable refrigerants may result in added cost of operation due to additional safety and sensor measures; however, added cost (or savings) was not considered in this methodology.

25. Although the SNAP regulations banning HFC-134a in new residential refrigerator-freezers allow alternatives with a GWP up to 630 by specific refrigerant listing (R-450A and R-513A with GWPs respectively of 601 and 630 are acceptable), new units manufactured beginning January 1, 2021 will very likely use R-600a (isobutane) as the refrigerant, with a GWP of 3.

26. Remaining ODS, such as HCFCs, will be phased out according to the current schedule agreed to by the Montreal Protocol. In the United States no new production or import of HCFC-22 will be allowed beginning January 1, 2020.

27. The HFC phase-down will not affect the emissions of other non-ODS F-gases such as PFCs, $SF_6$, $NF_3$, and $SO_2F_2$. Note that PFCs, $SF_6$, and $NF_3$ emissions in California are relatively low at 0.7 $MMTCO_2E$ annually in 2015 (1.7% of all F-gas emissions), while $SO_2F_2$ emissions are fairly significant at 5.2 $MMTCO_2E$ annually in 2015 (12.2% of all F-gas emissions). (The main use of $SO_2F_2$ is as a pesticide fumigant to control drywood termites.)

28. Emissions and reductions were modeled using both 100-year GWP and 20-year GWP values. No significant difference resulted in percent emissions change or percent reductions between 100-year and 20-year GWP values. The 20-year GWP values of HFCs range from less than the 100-year GWP values, to 3.5 times greater than the 100-year GWP value. The 20-year GWP value of HFCs ($CO_2$-equivalent weighted-average for all emissions) is on average, 2.25 times greater than the $CO_2$-equivalent weighted average using 100-year GWP values.

29. For the purposes of this HFC reductions methodology, we assume that HFC replacements are as energy efficient or more efficient than the high-GWP HFCs they replace. Therefore, the HFC phase-down will not inadvertently increase indirect GHG emissions from electricity and power usage.

    Please note that some stakeholders may disagree with this assumption, as available data show that some low-GWP equipment, particularly transcritical $CO_2$ in high ambient temperature environments may be less energy-efficient than the

HFC systems they replace.

However, developments since 2010 in transcritical $CO_2$ designed to optimize energy efficiency have proven to be as energy-efficient as traditional HFC refrigeration in almost all climates (DOE, 2015; ORNL, 2016). For very-high ambient temperature climates, additional energy-savings measures can be incorporated into refrigeration and AC systems that enable them to operate with the same efficiency, or minimal energy penalties compared to traditional HFC systems (ASHRAE, 2015; Danfoss, 2016; EIA, 2016; Emerson, 2015; Fritschi, et al., 2016; UNEP, 2016b).

In addition, industry reports that emerging technology using small charges of ammonia as a secondary refrigerant used to cool larger charges of $CO_2$ does not have energy penalties at high ambient temperatures.

Energy efficiency of low and lower-GWP refrigerants is currently the subject of a significant amount of research across the world. The in-depth analysis of the results of energy efficiency studies is beyond the scope of this particular methodology.

30. The methodology does not attempt to estimate indirect GHG emissions from the energy used to power refrigeration and air-conditioning systems. As previously noted, we do not expect the HFC phase-down to result in greater indirect GHG emissions from increased energy usage.

    A co-benefit of low-GWP refrigerants may be increased energy efficiency, lowering the lifecycle cost of operating equipment and reducing the total equivalent warming impact (TEWI) from the entire lifecycle of the equipment. For smaller hermetically sealed refrigeration equipment such as residential refrigerator-freezers, the electricity use can account for up to 97 percent of its lifecycle TEWI. For larger supermarket-sized refrigeration systems, the direct and indirect TEWI emissions are roughly equivalent (50% of the TEWI is from direct refrigerant emissions, and 50% of TEWI is from indirect emissions from electricity use) (IPCC/TEAP, 2006). However, an in-depth energy analysis of low-GWP refrigerants compared to high-GWP refrigerants is beyond the scope of this particular methodology.

## 5. EMISSIONS REDUCTIONS SCENARIOS

### SCENARIOS H1 and H2: Historical ODS Reductions Scenarios

In these scenarios, historical consumption and emission trends from the two national ODS phase-downs (Class I ODS primarily CFCs, and Class II ODS primarily HCFCs) in the United States are used to estimate the impact of the Kigali Amendment on future HFC emissions. Consumption and emissions data are from reports published by the

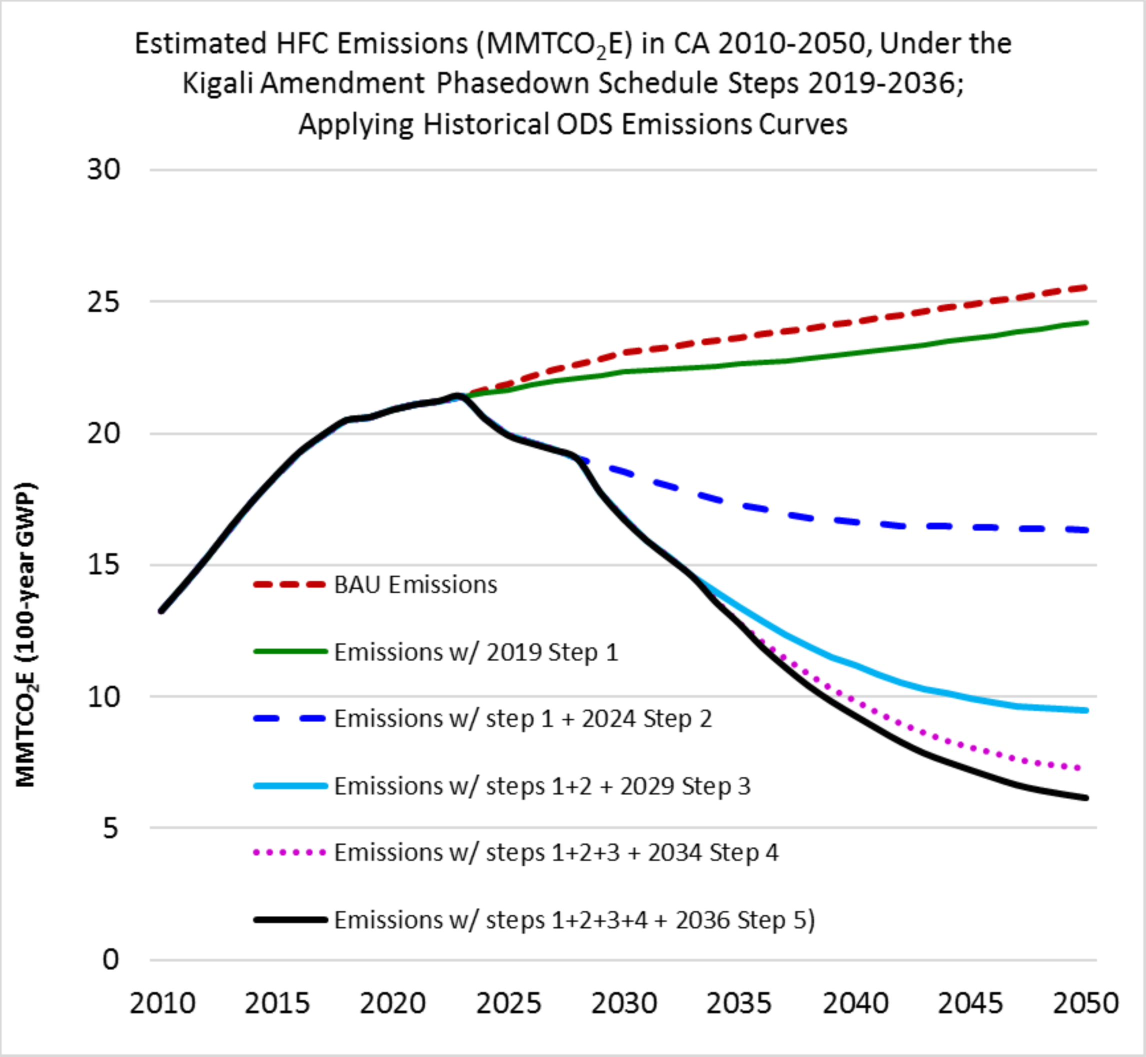
U.S. EPA and the UNEP (Montreal Protocol) Ozone Secretariat (U.S. EPA, 2017b, 2017c, and UNEP, 2017b). No specific assumptions are made on the average GWP of new equipment, or number of retrofits and the replacement GWP value of the new F-gas. However, the emissions data will inherently reflect and include all changes (from BAU) in the GWP values used in new equipment, and will reflect all retrofits from ODS and high-GWP refrigerants to different refrigerants. Although the actual GWP of replacement refrigerant to ODS refrigerant is not needed to apply historical reductions curves, it is most likely that the replacement refrigerant was less ozone-depleting, with a lower-GWP than CFCs, and a higher GWP than HCFC-22. For example, CFC-12 (GWP 10900) was often replaced by HCFC-22 (GWP 1810), and recently HCFC-22 has been replaced by the HFC blend R-404A (GWP of 3922). The historical emissions also reflect all stockpiling (or destruction) of refrigerants, and the recovery and re-use or recycling rates of refrigerants.

The primary modeling approach here takes the reductions curve of each of the two ODS phase-downs and applies it repeatedly to each of the five separate HFC phase-down steps, creating a wave-like pattern. Reductions as a result of meeting a given phase-down step may be locked into new low-GWP equipment, and reductions continue for many years from a given step, or even a given year of equipment production. Therefore, the impact of a given phase-down step will overlap with one or more of the next phase-down steps, and the emissions reductions from all the steps are additive and are aggregated for each calendar year.

For example, the reductions impacts from a near-total phase-out as occurred for CFCs, is estimated for year 1 of the phase-out, through the present, and projected forward until negligible CFC emissions occur. The HCFC-22 phase-down (still in progress) uses production-consumption data, which is compared to emissions. The results are a reductions curve, where for example, a 20 percent reduction in production-consumption (supply) beginning a specific year results in a differential emissions reductions curve where the reductions in refrigerant supply are not reflected immediately by equivalent reductions in emissions. The 20 percent decrease in supply will eventually result in a 20 percent decrease in emissions as equipment using HCFC-22 is retired or retrofitted, and the HCFC-22 refrigerant is leaked out, lost at equipment end-of-life, or destroyed.

The approach of applying the historical ODS reductions (in production-consumption) from an abrupt phase-out and applied to separate production-consumption phase-down steps of the Kigali Amendment results in an aggregation of what can be thought of as five separate “mini-phase-outs”, which are then aggregated together to show estimated lower emissions from overlapping effects of the separate phase-down steps. The additive nature of the emissions reductions caused by each production-consumption phase-down step is illustrated in the following figure.

## Figure 3. Estimated HFC Emissions (MMTCO₂E) in California from the Kigali Amendment HFC Phase-down Schedule; Applying Historical ODS Emissions Reductions Trends



The following equations H1 through H4 were used to estimate the potential lower HFC emissions as a result of the Kigali Amendment, by applying the historical ODS emissions reductions trends, or “curves”, to the HFC phase-down schedule.

### ***Equation (H1) HFC Emissions in a Given Year*** (MMTCO$_2$E)

$$HFC\ Emissions_n = (BAU\ Emissions_n) \times \left(1 - \sum_{n=2019}^{n} HFC\ Reductions_n(\%)\right)$$

where:

**HFC Emissions*n*** is the total HFC emissions in year n (MMTCO$_2$E).

**n** is a given calendar year.

**BAU Emissionsn** is BAU HFC emissions in year n (MMTCO$_2$E).

***HFC Reductionsn (%)*** is the reductions in HFC emissions from baseline achieved in a given year, n, as a result of the phase-down (as a percent of BAU).

### ***Equation (H2) HFC Reductions in a Given Year***

$$HFC\ Reductions_n(\%) = \sum_{Step\ 1}^{Step\ 5} Step\ Reductions_n\ (\%)$$

where:

***Step Reductionsn (%)*** is the aggregated reductions from all separate HFC phase-down steps for a given year n. The results are shown as percent of BAU. For example, a 10 percent reduction in emissions from BAU is equal to 90 percent BAU emissions.

### ***Equation (H3) HFC Phase-down Step Reductions***

$$Step\ Reductions_n\ (\%) = \Delta\ Allocation\ (\%) \times ODS\ Reduction\ Curve_m\ (\%)$$

where:

$\Delta$ ***Allocation (%)*** is the additional decrease in the HFC production and consumption allocation from the previous consumption step. For example, in the first step of the phase-down in 2019, the production-consumption allocation is 90% of baseline. In the second step in the 2024, the allocation is 60% of baseline. Therefore, the change in allocation from the first to second step of the phase-down is 30% (90% minus 60%).

**ODS Reduction Curve (%)** is the reduction in ODS emissions from baseline achieved in a given year, m, as a result of the ODS phase-down (as a percent of baseline).

***m*** is the relative year of the ODS phase-down which is equal to the number of years from the beginning of the current phase-down step to year n. For example, 2026 is two (2) years into the second HFC phase-down step. Therefore, m is equal to two (2) and this corresponds to the percent ODS reductions in year two (2) of the ODS phase-down.

For each phase-down step, sum reductions achieved each calendar year, from year 1 to the last year of the phase-down step, where the last year equals 20 years after the initial phase-down year. Based on ODS emissions data, the effects of each phase-down step last 20 years due to installation of reduced GWP refrigerant in equipment, which can be used on average 20 years (range of 10 years to 30 years), with measurable but negligible emissions more than 20 years after the phase-out of an F-gas.

### *Equation (H4)* ODS Reduction Curve (%)

$$ODS\ Reduction\ Curve_m\ (\%) = \frac{(ODS\ Emissions_{m-1} - \ ODS\ Emissions_m)}{(ODS\ Baseline\ Emissions)} \times 100\%$$

where:

***ODS Emissions$_{m-1}$*** is the ODS Emissions in year prior to year m of the ODS phase-down (MMTCO$_2$E).

***ODS Emissions$_m$*** is the ODS Emissions in year m of the ODS phase-down (MMTCO$_2$E).

***ODS Baseline Emissions*** is the baseline ODS emissions (MMTCO$_2$E).

The reductions curves for historical ODS emissions are shown in Tables 3 and 5.

Limitations of Historical ODS Data Models

The ODS reductions curves are likely to overestimate the speed at which HFC emissions reductions could occur, because the ODS phase-downs were more rapid than the HFC phase-down, and there were readily available substitutes for all emissions sectors using ODS (except medical dose inhalers). Additionally, HFCs will be phased down slowly, which may act as an incentive to continue using HFCs as long as possible for some end-users. Alternately, major price increases in HFCs could stimulate a faster transition away from HFC usage in new and retrofitted equipment.

### Scenario H1: Historical CFC Phase-out

This section describes additional information used to develop the CFC “reductions curve” as applied to the HFC phase-down.

Using U.S. EPA data, the following CFC emissions reductions graph was developed:

**Figure 4. CFC Consumption and Emissions (MMT$CO_2$E) in the U.S., 1990-2020**

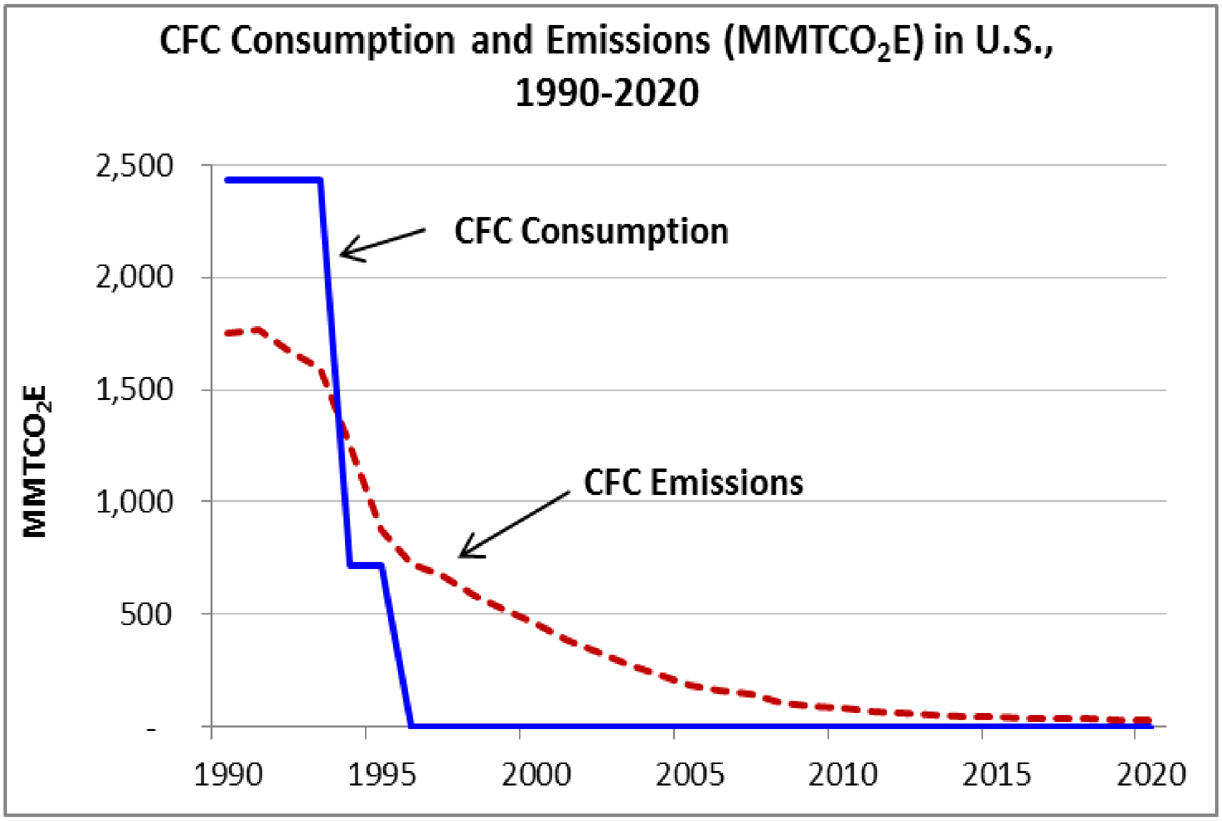


Figure source of data: CFC Consumption: UNEP (Montreal Protocol) Ozone Secretariat (UNEP, 2017b), with consumption converted from ozone-depletion potential (ODP) tonnes to MMT$CO_2$E. CFC emissions: Years 1990-2015 are from “U.S. EPA Greenhouse Gas Emissions and Sinks” (U.S. EPA, 2017b, 2017c). Years 2016 through 2020 are national CFC emissions (negligible) projections estimated by CARB (CARB, 2016a).

The production/consumption phase-out schedule of CFCs in the United States was as follows:

1975-1977: Following the discovery and acceptance that CFCs are depleting the ozone layer, many manufacturers voluntarily stop using CFC propellants in consumer product aerosols in the United States (Maxwell and Briscoe, 1997).

1978: The U.S. EPA ban CFCs as aerosol propellants in consumer product aerosols (exemptions made for medical dose inhalers and for aerosols used in limited technical uses) (U.S. EPA, 1990).

1987: The Montreal Protocol on Substances that Deplete the Ozone Layer (“Montreal Protocol”) international treaty designed to protect the ozone layer by phasing out the production of ozone depleting substances was agreed to on 26 August 1987, and entered into force on 26 August 1989.

1990: Excise tax on CFCs begins in the United States (IRS, 2007).

1993 - 1994: Production/consumption of CFCs cut 75 percent compared to baseline year 1986. Most refrigeration and AC manufacturers phase out CFC refrigerants from new production chillers, refrigerators, motor vehicle air conditioners, and other products two or more years before the 1996 CFC consumption phase-out (U.S. EPA, 2014a).

1995: Consumption/production of CFCs remains at 75 percent below baseline.

1996: Ban on all new production and consumption of CFCs.

Additional details on the phase-out of all Class I ODS are included in Appendix B.

Following a complete ban on production and consumption of all new CFCs, emissions of CFCs were reduced by 50 percent after five years, 75 percent after 10 years, and 90 percent after 15 years. A similar reductions curve could be applied to each separate step of the HFC phase-down. Note that if the historical ODS reductions are applied to the Kigali Amendment HFC phase-down schedule, the final 85 percent phase-down step beginning in 2036 would not result in equivalent emissions reductions until after 2050.

The following table shows measured CFC reductions in the United States following its phase-out (shown on following page to preserve table continuity).

## Table 3. Historical CFC Emissions Reductions.

| Year after CFC Phase-out | Calendar Year | Annual Emissions Reductions | Cumulative Reductions Below Baseline | Emissions as Percent of Baseline |
|---|---|---|---|---|
| 1 | 1995 | 15% | 15%[1] | 85% |
| 2 | 1996 | 11% | 26% | 74% |
| 3 | 1997 | 7% | 33% | 67% |
| 4 | 1998 | 6% | 39% | 61% |
| 5 | 1999 | 6% | 45% | 55% |
| 6 | 2000 | 5% | 50% | 50% |
| 7 | 2001 | 5% | 55% | 45% |
| 8 | 2002 | 5% | 60% | 40% |
| 9 | 2003 | 4% | 64% | 36% |
| 10 | 2004 | 4% | 68% | 32% |
| 11 | 2005 | 4% | 72% | 28% |
| 12 | 2006 | 3% | 75% | 25% |
| 13 | 2007 | 3% | 78% | 22% |
| 14 | 2008 | 3% | 81% | 19% |
| 15 | 2009 | 3% | 84% | 16% |
| 16 | 2010 | 2% | 86% | 14% |
| 17 | 2011 | 2% | 88% | 12% |
| 18 | 2012 | 2% | 90% | 10% |
| 19 | 2013 | 2% | 92% | 8% |
| 20 | 2014 | 1% | 93% | 7% |
| 21 | 2015 | 1% | 94% | 6% |
| 22 | 2016 | <1% | 95% | 5% |
| 23 | 2017 | <1% | 95% | 5% |
| 24 | 2018 | <1% | 96% | 4% |
| 25 | 2019 | <1% | 96% | 4% |
| 26 | 2020 | <1% | 97% | 3%[2] |

Table Notes:
1) Solvents are presumed to be emitted within the first year of their production, and solvents accounted for 17 percent of CFC emissions nationally in 1994, the year before the CFC ban; while solvents currently comprise less than two percent of HFC emissions. Therefore, the HFC solvent portion of all HFC emissions is 15 percent less of total emissions than the CFC solvent portion (17% - 2% = 15%). HFC reductions will not occur as rapidly as CFC reductions. Including all CFC solvents, actual first year CFC reductions were a substantial 30 percent less than BAU. For this HFC reductions methodology, we take

into account the discrepancy between the initial solvent portion of all CFC emissions (17 percent) versus the solvent portion of HFC emissions (2 percent), and revise the 30 percent first year emissions reductions down to 15 percent to better represent the mix of HFC compounds (30 percent original reductions - 15 percent differential between CFC and HFC solvents = 15 percent adjusted first year emissions reductions).

2) Negligible emissions of CFCs will continue as long as insulating foam with CFC-11 remains in use, and until the last CFC-12 refrigerator-freezer retires. In 2015, U.S. appliance recyclers reported 150,000 pounds of CFC-12 recovered from recycled refrigerator-freezers, all of which were at least 20 years old (U.S. EPA RAD Program, 2015).

Appendix B contains Table B3 illustrating how the CFC reductions curve is applied to each separate step of the HFC phase-down, with aggregated reductions.

Assessing the historical reductions of CFCs from the ODS phase-out: the following observations, analyses, and projections are made:

1) The CFC phase-out succeeded in reducing more than 90 percent of CFCs by year 15 of the phase-out.

2) Actual emissions reductions of CFCs are more rapid than those expected by the HFC phase-down. As a complete ban, CFC reductions would be expected to occur more quickly than the gradual approach to the HFC phase-down.

3) CFC emissions will not likely go to zero even 30 years after the total phase-out, due to the long lifetime of insulating foam in buildings, and the small numbers but long tail-end lifetime of equipment surviving longer than 30 years, such as some residential refrigerator-freezers and industrial equipment.

4) CFC reductions were accelerated by a 75 percent phase-down in production and consumption in the two years leading up to the total prohibition. Massive stockpiling was likely prevented or reduced, and equipment manufacturers had two extra years to develop equipment not requiring CFCs.

5) Significant illegal importation of CFCs into the United States continued after the phase-out (EIA, 2005; UNEP 2007). The official U.S. EPA GHG inventory does not appear to include illegal imports of CFCs or any ODS in their inventory. Including illegal imports data (not available) would increase the use and emissions of CFCs, while decreasing and slowing the reductions of CFCs.

6) CFC reductions were very likely accelerated by the imposition of an excise tax in 1990 on new production and import of CFCs. Because no similar taxes are anticipated on HFCs, the HFC reductions may not be as rapid as the historical ODS emissions reductions. Additionally, CFCs were completely banned after only two years of a 75 percent phase-down, leading to a rapid transition away from CFCs. Most refrigeration and AC manufacturers stopped using CFC refrigerants in the new production of chillers, refrigerators, motor vehicle air conditioners, and other products two or more years before the 1996 CFC consumption phase-out. Unlike CFCs, HFCs will be gradually

phased down over 17 years, leading to a relatively long time for equipment manufacturers and end-users to transition away from high-GWP HFCs.

7) A total phase-out is more likely to force a rapid market transition than an incremental phase-down. Therefore, the HFC phase-down may result in emissions reductions adhering very close to the intended phase-down caps, but not exceeding the supply reductions schedule (10 percent, 40 percent, 70 percent, 80 percent, and 85 percent).

8) Recycling Refrigerants: CFC usage and emissions post-phase-out were very likely prolonged because of the relative ease of recycling pure F-gas compounds (CFC-11, CFC-12, CFC-113, CFC-114, and CFC-115). HFC recycling is expected to be less than the amount that occurred for CFCs and the commonly used Class II ODS, HCFC-22, due to the predominance of HFC blends used as refrigerants. At this time, refrigerant blends cannot be economically recycled and reconstituted to original mixture specifications.

An exception for HFCs is HFC-134a, used as a pure compound in vehicle air-conditioning, residential refrigerator-freezers, some industrial process cooling, and chillers used for comfort cooling in large buildings. Emissions of HFC-134a (not otherwise used in blends) in California in 2016 were estimated to be 42 percent of all HFCs emitted by weight (10.8 million lbs. of a total 25.7 million lbs.), and 36 percent of all HFCs by $CO_2$-equivalents (7.0 $MMTCO_2E$ of a total 19.3 $MMTCO_2E$). The American Carbon Registry estimates that less than 9 percent of HFCs are recovered and recycled, and that only the pure compound of HFC-134a is recycled to be used again (ACR, 2015).

Refrigerant distribution, recovery, and reclamation records are provided to the CARB Refrigerant Management Program annually. According to reported data, only two percent of HFC-134a sold or distributed is eventually recovered for reclamation (CARB, 2016b).

9) The CFC reductions curve described in this document agrees closely with estimated HFC emissions reductions from an HFC phase-down model developed by Velders, et al., 2009; and Velders, et al., 2014. The close agreement between the "Velders Reduction Curve" and the ODS reductions curve may be due to the reliance of both methodologies on historical ODS consumption and reductions used to predict likely HFC reductions from phase-down schedules.

### Scenario H2: Ongoing HCFC-22 Phase-out

In addition to the historical CFC reductions as a result of its phase-out, the historical and ongoing HCFC-22 consumption phase-down and resulting emissions reductions provides a useful example for estimating potential HFC reductions as a result of the Kigali Amendment.

HCFC-22 is the most common refrigerant used today, and is a Class II ODS, a “mildly” ODS with an ozone depletion potential (ODP) of 0.055 compared to an ODP of 1.0 for CFC-11 and CFC-12. As a result of HCFC-22’s lower ODP, it was allowed to be used in almost unlimited amounts until 2010 in the United States, when the total ODP-tonnes allocation of production/consumption continued to be phased down by the U.S. EPA under the Montreal Protocol amendment to accelerate the phase-down of HCFCs.

The following table shows the phase-down schedule for new production/consumption of HCFC-22 in the United States.

**Table 4. HCFC-22 Consumption and Allocation Amounts in Metric Tonnes.**

| Year | HCFC-22 Consumption Allocation in Metric Tonnes[1] | HCFC-22 Consumption Allocation as percent of baseline |
|---|---|---|
| 1995 and earlier | No allocation rules | N/A |
| 1996-2009 | 137,858 annually[2] | 100% (baseline) |
| 2010[3] | 57,762 | 41.9% |
| 2011 | 44,115 | 32.0% |
| 2012 | 24,401 | 17.7% |
| 2013 | 24,814 | 18.0% |
| 2014 | 19,576 | 14.2% |
| 2015 | 10,000 | 7.0% |
| 2016 | 8,000 | 5.6% |
| 2017 | 6,000 | 4.2% |
| 2018 | 4,000 | 2.8% |
| 2019 | 2,000 | 1.4% |
| 2020+ | 0 | 0% |

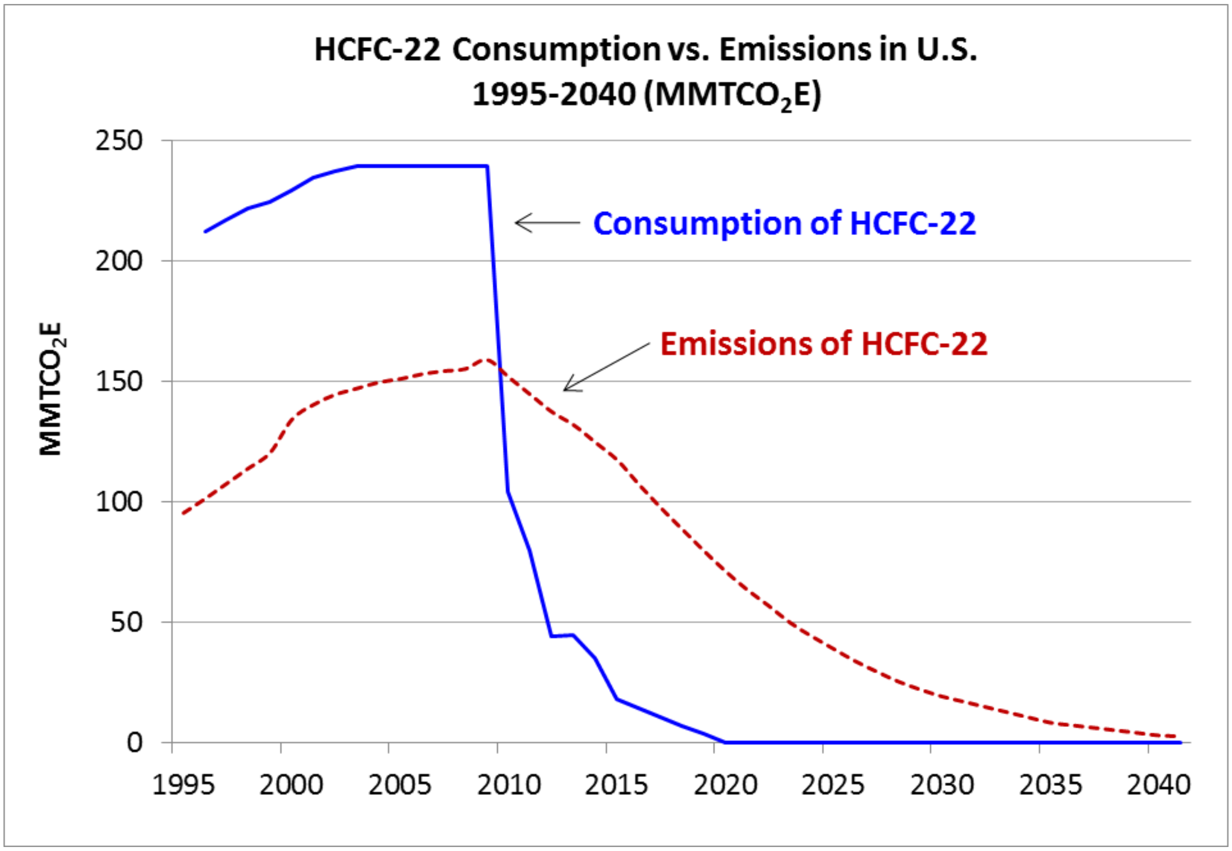
Table Notes:
1) Data source: U.S. EPA, 2014b, "Memorandum: Overview of the Final Rule for HCFC Allowances in 2015-2019”, Federal Register 2003 and 2014.

2) From 1996 through 2002, the allocation may have exceeded the actual consumption in the United States by 10 to 15 percent. From 2003 through 2020, the allocation and consumption are assumed to be equivalent.

3. Beginning January 1, 2010, HCFC-22 was prohibited in all new equipment manufactured or imported into the United States. Some air-conditioning units continued to be shipped into the U.S. containing no refrigerants, but were distinctly designed to use HCFC-22, in order to exploit an exemption in the SNAP rule that allowed the manufacture or import of new “maintenance” components designed to use HCFC-22. The units designed to use HCFC-22 were “direct replacement outside condensing units”, which technically are not the entire AC unit but are one of the major components. The exemption known as the “dry-ship R-22 unit” ended January 1, 2016 by U.S. EPA regulation (Design Air, 2016).

Using historical emissions records for HCFC-22, and applying BAU emissions to future emissions (Gallagher, et al., 2014), we can show the relationship between the HCFC-22 consumption phase-down and the intended emissions reductions that are delayed by years to decades (see following figure):

**Figure 5. HCFC-22 Consumption vs. Emissions in the U.S., 1995 – 2040 (2015-2040 projected).**



The HCFC-22 reductions curve is applicable to future HFC emissions reductions rates. However, the HCFC-22 reductions may occur at a faster rate than HFC reductions for at least four reasons:

1) The initial phase-down step in 2010 coincided with a near-total ban on HCFC-22 in new equipment – no similar HFC bans are mandated by the Kigali Amendment.

2) The 2010 phase-down step for HCFC-22 of 58 percent reduction in consumption was a strong market disruption signal that HCFC-22 was becoming scarcer, and therefore, existing equipment may have to be retrofitted, or retired earlier than planned.

3) The rapid phase-down of HCFC-22 led to a real or perceived market shortage of refrigerant to maintain existing equipment, leading to steep price increases in the

refrigerant, further incentivizing equipment operators to reduce leaks and/or transition away from HCFC-22 in existing equipment (ACHR, 2016).

4) New HCFC-22 will be completely phased out by January 1, 2020, just ten years after the 2010 phase-down. In comparison, the HFC phase-down will take place over 17 years; with a 15 percent consumption level remaining. The incentives to move away from HFCs are not as clear or strong as are the incentives to move away from continued HCFC-22 usage.

The following table shows the rate of HCFC-22 reductions from the phase-down thus far, with projected reductions following the BAU emissions methodology described in Gallagher, et al., 2014. Note that because the HCFC phase-down occurs over ten years, we have used the average rate of reductions achieved from each phase-down step. The following rate of reductions for HCFC-22 can be applied to each phase-down step of the Kigali Amendment.

**Table 5. Historical and Projected HCFC-22 Emissions Reductions.**

| Year of HCFC-22 Phase-out | Calendar Year | Annual Emissions Reductions by Percent | Cumulative Reductions by Percent Below Baseline Emissions | Emissions as Percent of Baseline |
|---|---|---|---|---|
| 1 | 2010 | 6% | 6% | 94% |
| 2 | 2011 | 6% | 12% | 88% |
| 3 | 2012 | 6% | 18% | 82% |
| 4 | 2013 | 6% | 24% | 76% |
| 5 | 2014 | 7% | 31% | 69% |
| 6 | 2015 | 7% | 38% | 62% |
| 7 | 2016 | 8% | 46% | 54% |
| 8 | 2017 | 7% | 54% | 46% |
| 9 | 2018 | 7% | 61% | 39% |
| 10 | 2019 | 7% | 67% | 33% |
| 11 | 2020 | 6% | 73% | 27% |
| 12 | 2021 | 6% | 79% | 21% |
| 13 | 2022 | 4% | 83% | 17% |
| 14 | 2023 | 4% | 87% | 13% |
| 15 | 2024 | 3% | 91% | 9% |
| 16 | 2025 | 3% | 93% | 7% |
| 17 | 2026 | 3% | 96% | 4% |
| 18 | 2027 | 2% | 98% | 2% |

| Year of HCFC-22 Phase-out | Calendar Year | Annual Emissions Reductions by Percent | Cumulative Reductions by Percent Below Baseline Emissions | Emissions as Percent of Baseline |
|---|---|---|---|---|
| 19 | 2028 | 1% | 99% | 1% |
| 20 | 2029 | <1%% | 99%+ | <1%% |
| 21 | 2030 | <1%% | 99%+ | negligible |
| 22 | 2031+ | <1%% | 99%+ | negligible |

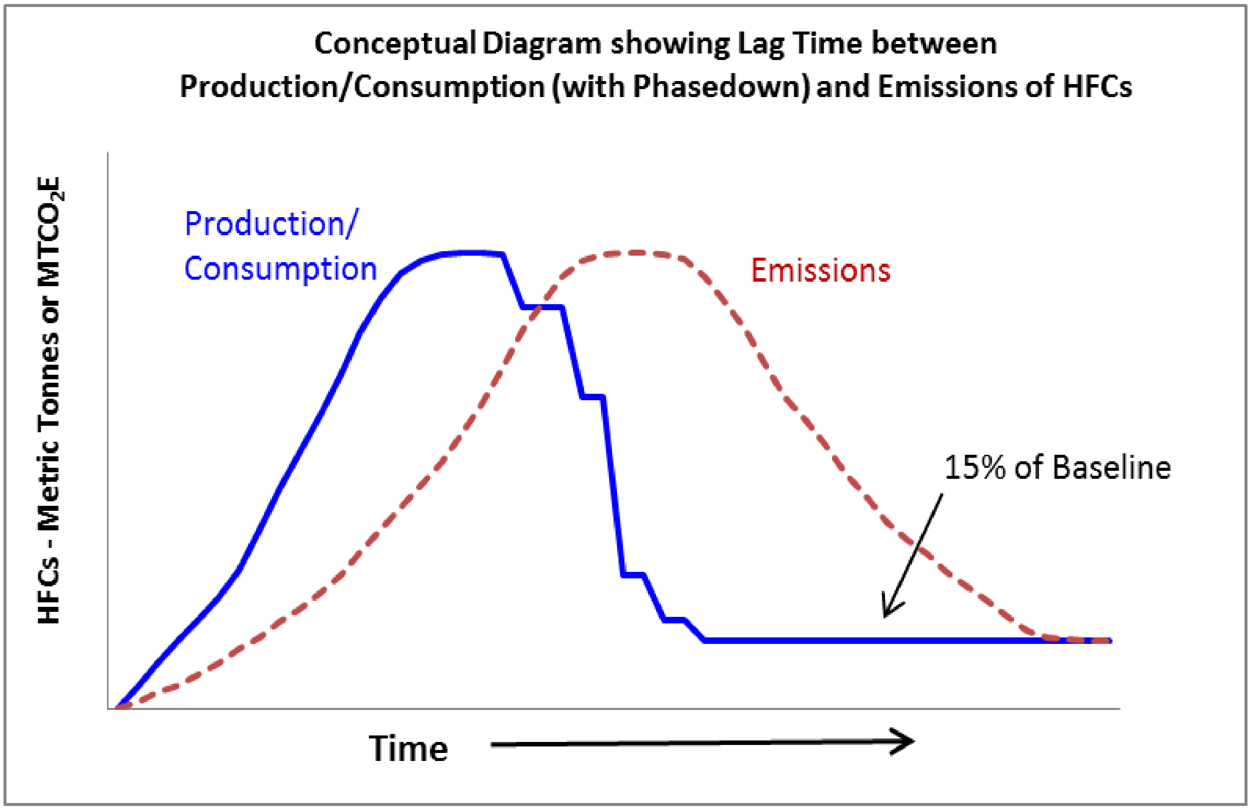
If we compare the reduction rates of HCFC-22 to CFCs, we see that the CFC emissions were reduced more rapidly than HCFC-22 emissions are being reduced (after mathematically normalizing for the relative reduction rates of a 3-year phase-out of CFCs versus a ten-year incremental phase-down of HCFC-22). The reasons may include the early voluntary transitions, the tax, and the faster phase-out or ban of CFCs compared to the lengthier phase-down of HCFC-22, which created a clear deadline for conversion providing a greater incentive to stop using CFCs more quickly than HCFC-22.

HFC emissions reductions trends and rates will very likely reflect those of HCFC-22 more so than CFCs. However, HFC reductions rates are expected to be slower than the reductions that have occurred either for CFCs or for HCFCs; reasons include the following:

- A lower percentage of voluntary conversion has taken place for HFC equipment,
- No HFC tax has been instituted,
- Longer phase-down schedule for HFCs, and
- HCFC-22 equipment was commonly retrofitted with much higher GWP HFC replacements (R-404A or R-507) until January 2017 - thus increasing the installed base of HFC equipment more rapidly than normal annual growth and simple replacement of retired equipment with new equipment.

From the CFC and HCFC data showing the relationship between consumption, a phase-out, and resulting emissions reductions, the following conceptual diagram can help to visualize HFC reductions as a result of the phase-down in developed countries. Production/consumption of HFCs will stabilize at 15 percent of baseline beginning in 2036. Emissions will eventually stabilize at the 15 percent of the baseline as well, although it could take several decades.

**Figure 6. Conceptual Diagram showing Lag Time between Production/Consumption (with Phase-down) and Emissions of HFCs.**



<u>Applying CFC and HCFC phase-out and phase-down reduction rates to future HFC reductions</u>:

To apply the historical ODS reductions curves, the phase-down should be thought of as a series of distinct steps. For reference, the HFC phase-down schedule is shown again.

**Table 6. HFC Phase-down Schedule for Developed Countries.**

| Year | Production/Consumption Cap | Reductions in Production/Consumption |
|---|---|---|
| 2017-2018 | None | None |
| 2019 | 90% | 10% |
| 2024 | 60% | 40% |
| 2029 | 30% | 70% |
| 2034 | 20% | 80% |
| 2036 | 15% | 85% |

We apply the historical reduction curves to each step of the phase-down, with years 2019-2023 set to zero reductions, and beginning reductions in year 2024. Because each phase-down step takes many years to achieve its reductions goals, reductions from phase-down steps overlap in time and are aggregated.

Our analysis indicates that the baseline set by the Kigali Amendment will be approximately equal to the demand for HFCs (in the United States and in California) in the first few years after the initial phase-down step in 2019. U.S. EPA SNAP Rule 20 (July 2015) and Rule 21 (December 2016) effectively reduce the demand for HFCs below the previously expected BAU demand, rendering the first 10 percent phase-down reduction redundant. The first meaningful phase-down in HFC production and consumption is not likely to begin until 2024, just six years prior to California’s 2030 goal. HFC emissions reductions cannot occur until the demand for HFCs again reaches or exceeds the available supply (officially limited by the phase-down but including any additional sources such as stockpiles and illegal imports). Therefore, the historical reduction curves are set to zero reductions for the phase-down years of 2019-2023, with meaningful HFC emissions reductions beginning in year 2024, the second step of the phase-down. Additional details are provided in Appendix F, “Further Background on the Kigali Baseline”, and Appendix H, “Supply versus Demand: Initial HFC Supply Cap is Greater than Business-as-Usual (BAU) Demand of HFCs”.

The following table shows the HFC emissions in California if the reductions were to follow the historical CFC emissions reductions rates.

**Table 7. HFC Emissions ($MMTCO_2E$) in CA using historical CFC reductions scenario.**

| Year | BAU Emissions in CA w/o Kigali | Annual Reductions by % (“reduction curve” applied to each step of phase-down schedule) | Annual reductions additional to BAU | Post-Kigali Emissions in CA |
|---|---|---|---|---|
| 2018 | 20.5 | 0% | 0.0 | 20.5 |
| 2019 | 20.6 | 0% | 0.0 | 20.6 |
| 2020 | 20.9 | 0% | 0.0 | 20.9 |
| 2021 | 21.1 | 0% | 0.0 | 21.1 |
| 2022 | 21.2 | 0% | 0.0 | 21.2 |
| 2023 | 21.4 | 0% | 0.0 | 21.4 |
| 2024 | 21.6 | 4.9% | 1.1 | 20.6 |
| 2025 | 21.9 | 4.9% | 1.9 | 19.9 |
| 2026 | 22.2 | 2.9% | 2.5 | 19.6 |
| 2027 | 22.4 | 1.9% | 3.1 | 19.4 |
| 2028 | 22.6 | 2.9% | 3.6 | 19.0 |

| Year | BAU Emissions in CA w/o Kigali | Annual Reductions by % (“reduction curve” applied to each step of phase-down schedule) | Annual reductions additional to BAU | Post-Kigali Emissions in CA |
|---|---|---|---|---|
| 2029 | 22.8 | 6.8% | 5.1 | 17.8 |
| 2030 | 23.1 | 6.3% | 6.3 | 16.8 |
| 2031 | 23.2 | 4.9% | 7.2 | 15.9 |
| 2032 | 23.3 | 3.4% | 8.0 | 15.3 |
| 2033 | 23.4 | 3.9% | 8.8 | 14.6 |
| 2034 | 23.5 | 5.3% | 9.9 | 13.6 |
| 2035 | 23.6 | 4.4% | 10.9 | 12.8 |
| 2036 | 23.8 | 5.3% | 11.9 | 11.9 |
| 2037 | 23.9 | 4.4% | 12.8 | 11.1 |
| 2038 | 24.0 | 3.9% | 13.6 | 10.4 |
| 2039 | 24.1 | 3.3% | 14.3 | 9.8 |
| 2040 | 24.2 | 3.1% | 14.9 | 9.3 |
| 2041 | 24.4 | 3.4% | 15.6 | 8.8 |
| 2042 | 24.5 | 2.9% | 16.2 | 8.3 |
| 2043 | 24.6 | 2.4% | 16.7 | 7.9 |
| 2044 | 24.8 | 2.9% | 17.2 | 7.5 |
| 2045 | 24.9 | 1.5% | 17.6 | 7.3 |
| 2046 | 25.0 | 1.9% | 18.0 | 7.0 |
| 2047 | 25.2 | 2.4% | 18.4 | 6.7 |
| 2048 | 25.3 | 1.5% | 18.8 | 6.5 |
| 2049 | 25.4 | 1.0% | 19.1 | 6.4 |
| 2050 | 25.6 | 1.5% | 19.3 | 6.3 |

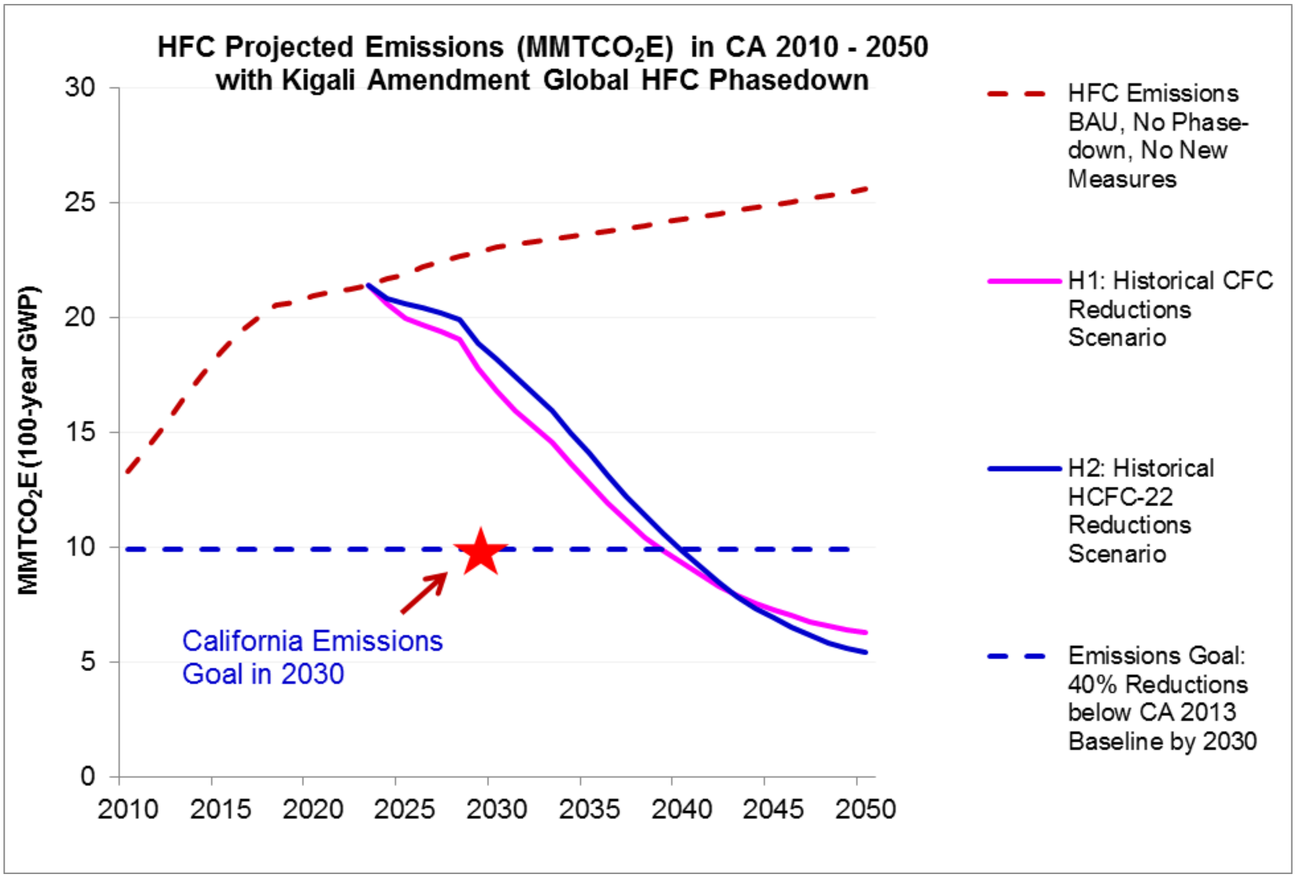
The historical HCFC-22 emissions reductions rates are also applied to the HFC phase-down to derive projected HFC emissions using the HCFC reductions trend scenario (reduction Scenario H2). (Table shown on following page to preserve continuity.)

**Table 8. HFC Emissions ($MMTCO_2E$) in CA using historical HCFC-22 reductions scenario.**

| Year | BAU Emissions in CA w/o Kigali | Annual Reductions by % ("reduction curve" applied to each step of phase-down schedule) | Annual reductions additional to BAU | Post-Kigali Emissions in CA |
|---|---|---|---|---|
| 2018 | 20.5 | 0% | 0.0 | 20.5 |
| 2019 | 20.6 | 0% | 0.0 | 20.6 |
| 2020 | 20.9 | 0% | 0.0 | 20.9 |
| 2021 | 21.1 | 0% | 0.0 | 21.1 |
| 2022 | 21.2 | 0% | 0.0 | 21.2 |
| 2023 | 21.4 | 0% | 0.0 | 21.4 |
| 2024 | 21.6 | 3.8% | 0.8 | 20.8 |
| 2025 | 21.9 | 2.7% | 1.3 | 20.6 |
| 2026 | 22.2 | 2.3% | 1.8 | 20.4 |
| 2027 | 22.4 | 2.0% | 2.3 | 20.2 |
| 2028 | 22.6 | 2.3% | 2.7 | 19.9 |
| 2029 | 22.8 | 6.0% | 4.0 | 18.9 |
| 2030 | 23.1 | 4.8% | 4.9 | 18.2 |
| 2031 | 23.2 | 4.3% | 5.8 | 17.4 |
| 2032 | 23.3 | 4.1% | 6.6 | 16.7 |
| 2033 | 23.4 | 3.9% | 7.5 | 15.9 |
| 2034 | 23.5 | 5.2% | 8.6 | 15.0 |
| 2035 | 23.6 | 4.8% | 9.6 | 14.1 |
| 2036 | 23.8 | 5.8% | 10.7 | 13.1 |
| 2037 | 23.9 | 4.8% | 11.7 | 12.2 |
| 2038 | 24.0 | 4.4% | 12.6 | 11.4 |
| 2039 | 24.1 | 4.3% | 13.5 | 10.6 |
| 2040 | 24.2 | 4.1% | 14.4 | 9.9 |
| 2041 | 24.4 | 4.4% | 15.2 | 9.1 |
| 2042 | 24.5 | 3.8% | 16.0 | 8.5 |
| 2043 | 24.6 | 3.4% | 16.8 | 7.8 |
| 2044 | 24.8 | 3.5% | 17.4 | 7.3 |
| 2045 | 24.9 | 2.5% | 18.0 | 6.9 |
| 2046 | 25.0 | 2.4% | 18.5 | 6.5 |
| 2047 | 25.2 | 2.8% | 19.0 | 6.1 |
| 2048 | 25.3 | 2.0% | 19.5 | 5.8 |
| 2049 | 25.4 | 1.7% | 19.9 | 5.6 |
| 2050 | 25.6 | 1.7% | 20.1 | 5.4 |

The following graph shows the post-Kigali phase-down emissions compared to BAU emissions in California, using historical ODS reductions data.

**Figure 7. HFC Projected Emissions in CA with Global HFC Phase-down, Historical CFC, and HCFC-22 emissions reductions scenarios.**



If the HFC reductions were to follow the historical ODS reductions rates, the 2030 HFC reductions goal in California would not be met until the years 2039-2040 plus/minus three years.

## SCENARIO BC: Best-Case Reductions Scenario

To create an upper bound on the highest reductions expected and most rapid emissions reductions from an HFC phase-down, hypothetical reductions were modeled by assuming HFC end-use sectors would begin using low-GWP alternatives as soon as feasible. The term feasible is subjective by nature. In this scenario, the earliest feasible dates to produce and require low-GWP equipment (and materials) is shown in the following Table 9. For stationary refrigeration, we use a feasibility date of 2019 due to existence of many low-GWP systems already available. For stationary AC, we use a feasibility date of 2024 because the relevant codes and standards do not allow slightly flammable refrigerants for most end-uses (refrigerants with a GWP less than 750 are likely to be HFCs or HFO-HFC blends that are slightly flammable). We use the SNAP start dates for lower-GWP HFCs in new end-uses for light-duty MVAC, chillers, residential refrigerator-freezers, consumer product aerosol propellants, and insulating foam. We link the heavy-duty MVAC and transportation refrigeration sectors to equal the start date of light-duty MVAC.

We also assume in the best-case scenario that refrigeration equipment using refrigerants with very-high GWPs ≥ 2500 would begin to retrofit to refrigerants with GWPs < 2000. This best-case scenario is not likely due to the phase-down alone, but could occur as a result of separate measures prohibiting high-GWP refrigerants, or providing incentives to use low-GWP refrigerants in new equipment and in retrofits of existing equipment. Emissions sectors were modeled using the standard CARB F-gas emissions model (described in Appendix A), except the GWP of the end-use sectors were changed as shown in the following table.

**Table 9. Baseline GWPs of Equipment and Feasible Lower GWPs.**

| General End-Use Sector | New Equipment Refrigerant BAU, pre-Kigali | GWP of BAU Refrigerant | New Equipment Refrigerant Post-Kigali [1] | GWP of New Refrig-erant | Low-GWP Equipment start date used |
|---|---|---|---|---|---|
| All Stationary Refrigeration, Commercial and Industrial | R-407A | 2107 | $CO_2$, $NH_3$, hydrocarbons, pure HFOs[2] | < 150 | 2019 best estimate |
| Residential Refrigerator-Freezer | HFC-134a until 2021, then R-600a (isobutane) due to SNAP rules | 1430 for HFC-134a; and 3 for R-600a | R-600a (isobutane) | 3 | 2021 required by SNAP |
| Commercial Chillers used for Air-conditioning | HFC-134a | 1430 | HFO-1233zd or HFO-1234ze(E)[3] | < 10 | 2024 required by SNAP |
| Commercial AC (non-chiller) and Residential AC | R-410A | 2088 | HFC-32 or HFO-HFC blends | < 750 | 2024 best estimate |

| General End-Use Sector | New Equipment Refrigerant BAU, pre-Kigali | GWP of BAU Refrigerant | New Equipment Refrigerant Post-Kigali [1] | GWP of New Refrig-erant | Low-GWP Equipment start date used |
|---|---|---|---|---|---|
| Light-duty MVAC | HFC-134a until Model Year 2021, then low-GWP required | 1430 for HFC-134a; < 10 for HFO-1234yf | HFO-1234yf or $CO_2$ | < 10 | Model Year 2021 required by SNAP |
| Heavy-duty MVAC | HFC-134a | 1430 | HFO-1234yf or $CO_2$ | < 10 | Model Year 2021 best estimate |
| Transport Refrigeration | R-404A | 3922 | < 150 ($CO_2$, HFOs) [2] | | 2021 best estimate |
| Insulating Foam | HFC-134a and HFC-245fa ($CO_2$ and hydrocarbons also used extensively) | GWPs in order of list: 1430, 725, 1, <10 | HFCs replaced by HFOs, $CO_2$, or hydrocarbons, by SNAP prohibitions | < 15 | SNAP rules 2019 through 2025 depending upon end-use |
| Consumer Product Aerosol Propellants | Most propellant is already low-GWP hydrocarbons. For F-gas propellants, HFC-152a used in 87% of uses, HFC-134a used in remaining requiring an F-gas. | 124 for HFC-152a, and 1430 for HFC-134a | HFC-152a use continues and HFC-134a is replaced by HFOs | 124 for HFC-152a, and < 10 for HFOs | 2016 for SNAP-covered propellants, and 2019 for remaining HFC-134a exemptions (best estimate) |

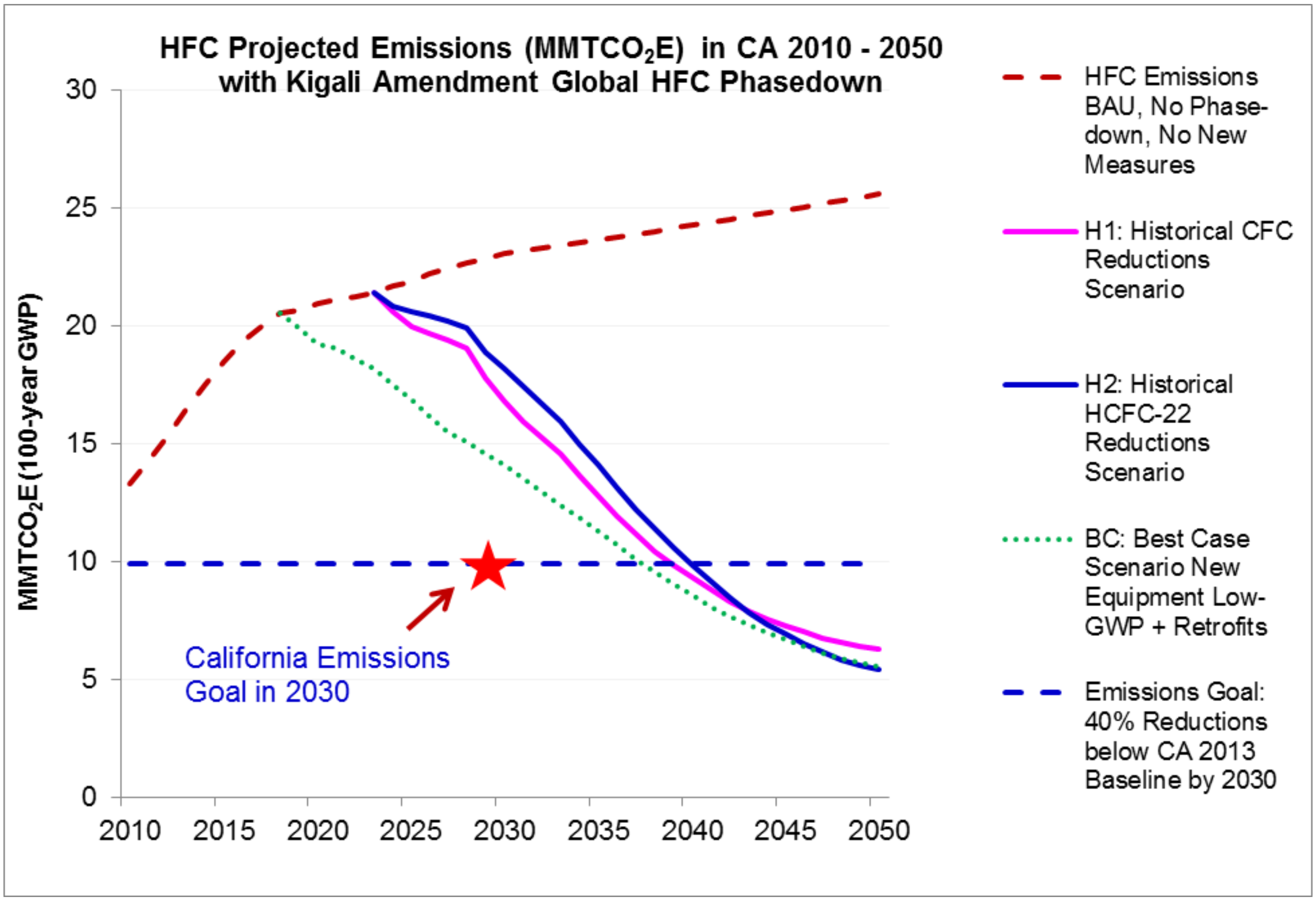
Table Notes:
1) To simplify modeling and avoid over-estimating potential reductions, “< 150 GWP” for refrigeration is modeled using a GWP of 150; and “< 750 GWP” for air-conditioning is modeled using a GWP of 750.

2) Pure HFOs are included as hypothetical replacements to high-GWP HFCs. At this time, using pure HFOs in commercial refrigeration equipment and transport refrigeration does not appear feasible, except in large chillers often used for air-conditioning and some refrigeration uses. Blends of HFO-HFC refrigerants are currently in use in new equipment and retrofits, with additional blends being developed. However, the < 150 GWP alternatives were modeled as best case outcomes, not as a most likely scenario.

3) Best case scenario for chillers is shown. SNAP listings allow R-513A with a GWP of 630.

The following figure shows estimated HFC reductions under a “best case” scenario for a rapid transition to low-GWP alternatives in new equipment.

**Figure 8. HFC Projected Emissions in CA with Global HFC Phase-down, Best Case Scenario, Rapid Transition to Low-GWP for New Equipment + Retrofits.**



The following is a tabular representation of the best-case scenario emissions shown in the graph above (shown on following page to preserve table continuity).

**Table 10. HFC Emissions in CA using hypothetical "Best Case" Reductions scenario – Low-GWP New Equipment and Retrofits of Existing Equipment**

| Year | BAU Emissions in CA w/o Kigali | Absolute Annual Reductions from peak emissions ("reduction curve") | Annual reductions additional to BAU | Post-Kigali Emissions in CA |
|---|---|---|---|---|
| 2018 | 20.5 | 0% | 0.0 | 20.5 |
| 2019 | 20.6 | 3.7% | 0.8 | 19.9 |
| 2020 | 20.9 | 4.5% | 1.7 | 19.2 |
| 2021 | 21.1 | 2.0% | 2.1 | 19.0 |
| 2022 | 21.2 | 2.8% | 2.7 | 18.6 |
| 2023 | 21.4 | 2.7% | 3.2 | 18.2 |
| 2024 | 21.6 | 4.5% | 4.1 | 17.5 |
| 2025 | 21.9 | 4.3% | 5.0 | 16.8 |
| 2026 | 22.2 | 4.7% | 6.0 | 16.2 |
| 2027 | 22.4 | 4.6% | 7.0 | 15.5 |
| 2028 | 22.6 | 2.9% | 7.5 | 15.1 |
| 2029 | 22.8 | 3.5% | 8.3 | 14.6 |
| 2030 | 23.1 | 3.4% | 9.0 | 14.1 |
| 2031 | 23.2 | 3.4% | 9.7 | 13.5 |
| 2032 | 23.3 | 3.3% | 10.4 | 12.9 |
| 2033 | 23.4 | 3.2% | 11.0 | 12.4 |
| 2034 | 23.5 | 3.3% | 11.7 | 11.8 |
| 2035 | 23.6 | 3.4% | 12.4 | 11.3 |
| 2036 | 23.8 | 3.4% | 13.1 | 10.7 |
| 2037 | 23.9 | 3.6% | 13.8 | 10.1 |
| 2038 | 24.0 | 3.1% | 14.5 | 9.5 |
| 2039 | 24.1 | 3.0% | 15.1 | 9.1 |
| 2040 | 24.2 | 3.1% | 15.7 | 8.5 |
| 2041 | 24.4 | 2.9% | 16.3 | 8.1 |
| 2042 | 24.5 | 2.8% | 16.9 | 7.6 |
| 2043 | 24.6 | 2.3% | 17.4 | 7.3 |
| 2044 | 24.8 | 2.2% | 17.8 | 7.0 |
| 2045 | 24.9 | 2.1% | 18.2 | 6.7 |
| 2046 | 25.0 | 2.1% | 18.7 | 6.4 |
| 2047 | 25.2 | 2.0% | 19.1 | 6.1 |
| 2048 | 25.3 | 1.8% | 19.4 | 5.9 |
| 2049 | 25.4 | 1.6% | 19.8 | 5.7 |
| 2050 | 25.6 | 1.5% | 20.1 | 5.5 |

In addition to new low-GWP equipment reductions, the best case scenario also includes the potential retrofits of equipment using very high-GWP refrigerants (GWP 2500 or greater), replacing the high-GWP HFC refrigerant blends R-404A (GWP 3922) and R-

507 (GWP 3985) with R-407A (GWP 2107), R-407F (GWP 1825), or one of the new HFO-HFC blends that are lower-GWP "near drop-in" replacements: R-448A (GWP 1386) or R-449A (GWP 1396). We model a hypothetical annual retrofit rate of 1/8 of equipment (using refrigerants with a GWP 2500 or greater) will retrofit to a representative (non-specific) refrigerant with a GWP of 1500, over 8 years of retrofitting, at which time no refrigeration equipment will remain with a refrigerant with a GWP of 2500 or greater.

Without additional regulations the initial cost of $40,000 to $80,000 per retail food retrofit would be a barrier to widespread retrofitting, although energy efficiency gains could result in a neutral cost over equipment lifetime (Babiloni, et al., 2015; EERE, 2015). Additionally, the high cost of HCFC-22 and potentially higher cost of HFCs in the future would act as an economic incentive to retrofit. For reference, the reductions from retrofits are included in Appendix D, "Impact on Emissions from Servicing Demand and Retrofits".

In this scenario, the impact of new low-GWP equipment and lower-GWP retrofits reduces the demand for high-GWP HFCs (both in new equipment and for servicing existing equipment) at a rate that meets or exceeds the phase-down schedule. Such an outcome is doubtful without measures additional to the global HFC phase-down.

### SCENARIO WC: Worst-Case, Slow Transition to Low-GWP Alternatives

This scenario is called the "worst case" scenario (Scenario WC) because it represents the minimum emissions reductions we would expect under the Kigali phase-down in the absence of additional measures. The intent here is to bracket the historical ODS emissions reductions (curve) with a slower reductions scenario in addition to the faster (best case) scenario.

The worst-case scenario takes the theoretical maximum allowable consumption to achieve Kigali targets by simply reducing GWPs of refrigerants used in new equipment (for each end use) according to the Kigali step down schedule. Servicing demand of refrigerant (through the first ten years of the phase-down) to replace refrigerant leaked from existing equipment is primarily from stockpiling of refrigerants prior to the phase-down, and from illegal imports of HFCs. Illegal venting of refrigerant at equipment end-of-life remains high for most end-use sectors. The recovery and recycling rate of refrigerants does not increase from current business-as-usual practices. Retrofits of existing equipment to lower-GWP refrigerants do not occur.

The main assumption we use here is that the shrinking allocation of high-GWP HFCs will only affect the types of refrigerants used in new equipment manufacture, and will not change the refrigerant usage (type or amount) used in existing equipment.

Although this scenario is theoretical and extremely unlikely, it may be useful as a way to illustrate the slowest HFC reductions and define the extreme latest date of meeting the state's HFC emissions reduction goals.

In this slow transition scenario, servicing demand of existing refrigeration and AC equipment could be met through potentially significant stockpiling of HFCs prior to the first phase-down in 2019 (no freeze on production or import of HFCs is in effect for developed countries in 2017 and 2018). Additionally, as illegal imports of ODS into the United States were common after new CFC production and import was banned in 1996 (EIA, 2005), significant illegal imports of HFCs into the state could occur without strict enforcement in place. If reclamation and recycling of refrigerants increases above current levels (which is not assumed), then reductions would be greater.

Reductions are modeled for each end-use sector. The only change from BAU is that we assume that new equipment manufactured is now constrained by a diminishing supply of high-GWP HFCs. Due to less high-GWP supply, manufacturers of new equipment are very likely to use lower-GWP refrigerants than BAU. It is expected that the manufacturers will take one of the three following paths in terms of using low-GWP refrigerants:

1) Transition directly from high-GWP to low-GWP refrigerants;
2) Transition from high-GWP to GWPs that while lower than BAU, are still considered relatively high-GWP or “mid-high” GWP values between 150 and 1500; or
3) No change in the high-GWP HFC refrigerants used historically.

Given that the actual GWPs used in new equipment for each end-use sector is very difficult to predict, it is assumed that the market producing new equipment solves this problem dynamically in a way that exactly uses available allocations.

Mathematically, this is modeled by reducing the average GWP of new equipment to an amount roughly equivalent to the HFC phase-down reductions in new HFC production/consumption.

For example, beginning 2024, the cap will be 40 percent less than the baseline, equaling a 40 percent reduction in the average GWP used in new equipment compared to BAU. In 2029, the average GWP for new equipment would be 70 percent less than BAU, reflecting the 70 percent cut in production and consumption, 80 percent less in 2034, and 85 percent less in 2036 and future years.

Assumptions and input factors used are listed below:

Annual leak rates, end-of-life loss rates, and refrigerant charge sizes are kept the same between baseline and projected emissions. Only the average GWP of the refrigerant changes.

The lifetime emissions were calculated for each emissions sector, using their specific mix of charge size, leak rates, and end-of-life loss rates.

Each sector was modeled using the average lower-GWP value for refrigerants/materials in new equipment. The following table shows BAU GWP values, and the new lower GWP values used in new equipment as a result of the phase-down.

**Table 11. GWP Values for BAU and Declining GWP Values (on average) for New Equipment due to HFC Phase-down. Production/Consumption Steps as listed in Kigali Agreement, no interim steps modeled.**

| | | **New GWP Values given the baseline refrigerant:** | | | | | |
|---|---|---|---|---|---|---|---|
| | | Cap: | 90% | 60% | 30% | 20% | 15% |
| **End-Use Sector** | **2016-2024 Baseline Refrigerant** | **BAU average** | **2019 new** | **2024 new** | **2029 new** | **2034 new** | **2036 new** |
| **Stationary Air-conditioning Sectors** | | | | | | | |
| Unitary A/C small (50-200 lbs.) | R-134a (20%); R-407C (35%); R-410A (45%) | 1,847 | 1,662 | 1,108 | 554 | 369 | 277 |
| Unitary A/C central less than 50 lbs. | R-134a (20%); R-407C (35%); R-410A (45%) | 1,847 | 1,662 | 1,108 | 554 | 369 | 277 |
| Window AC units commercial | R-407C (30%); R-410A (70%) | 1,994 | 1,794 | 1,196 | 598 | 399 | 299 |
| Residential AC central | R-407C (5%); R-410A (95%) | 2,072 | 1,865 | 1,243 | 622 | 414 | 311 |
| Window AC units residential | R-407C (30%); R-410A (70%) | 1,994 | 1,794 | 1,196 | 598 | 399 | 299 |
| **Stationary Refrigeration Sectors [1]** | | | | | | | |
| Centralized system large 2,000-lb.+ | R-407A | 2,107 | 1,896 | 1,264 | 632 | 421 | 316 |
| Centralized system medium 200-2,000 lbs. | R-407A (96%); R-407C (2%); HFC-134a (2%) | 2,087 | 1,878 | 1,252 | 626 | 417 | 313 |
| Cold storage large 2,000-lb.+ | R-404A or R-507 | 3,954 | 3,558 | 2,372 | 1,186 | 791 | 593 |
| Cold storage medium 200-2,000 lbs. | R-404A or R-507 | 3,954 | 3,558 | 2,372 | 1,186 | 791 | 593 |
| Process cooling large 2,000-lb.+ | R-134a (65%; R-410A (4%); R-404A (11%); R-507 (20%) | 2,244 | 2,020 | 1,346 | 673 | 449 | 337 |

| | | New GWP Values given the baseline refrigerant: | | | | | |
|---|---|---|---|---|---|---|---|
| | | Cap: | 90% | 60% | 30% | 20% | 15% |
| **End-Use Sector** | **2016-2024 Baseline Refrigerant** | **BAU average** | **2019 new** | **2024 new** | **2029 new** | **2034 new** | **2036 new** |
| Refrigerated condensing units small (50-200 lbs.) | R-134a (24%); R-407A (36%); R-407C (40%) | 1,811 | 1,630 | 1,087 | 543 | 362 | 272 |
| Refrigerated condensing units less than 50 lbs. | R-134a (24%); R-407A (36%); R-407C (40%) | 1,811 | 1,630 | 1,087 | 543 | 362 | 272 |
| **Mobile, Transport, Solvent, and Propellant Sectors**[2] | | | | | | | |
| MVAC Bus | R-134a | 1,430 | 1,287 | 858 | 429 | 286 | 215 |
| MVAC Heavy Duty (HD) (non-bus) | R-134a | 1,430 | 1,287 | 858 | 429 | 286 | 215 |
| MVAC Off-Road | R-134a | 1,430 | 1,287 | 858 | 429 | 286 | 215 |
| Transport Refrigerated Units (TRUs) | R-404A (90%); R-134a (10%) | 3,673 | 3,306 | 2,204 | 1,102 | 735 | 551 |
| Refrigerated Shipping Containers (RSCs) | R-134a (85%); R-404A (15%) | 1,804 | 1,623 | 1,082 | 541 | 361 | 271 |
| Ships - marine vessels | R-134a (65%); R-404A (19%); R-507 (10%); R-407C (6%) | 2,187 | 1,968 | 1,312 | 656 | 437 | 328 |
| Industrial solvents (non-semiconductor) | HFC-245fa (97%); HFC-4310mee (2%); HFC-365mfc (1%) | 1,040 | 936 | 624 | 312 | 208 | 156 |
| Consumer product aerosol propellants | HFC-152a (86.7%); R-134a (13.0%); HFC-4310mee (0.3%) | 296 | 266 | 177 | 89 | 59 | 44 |

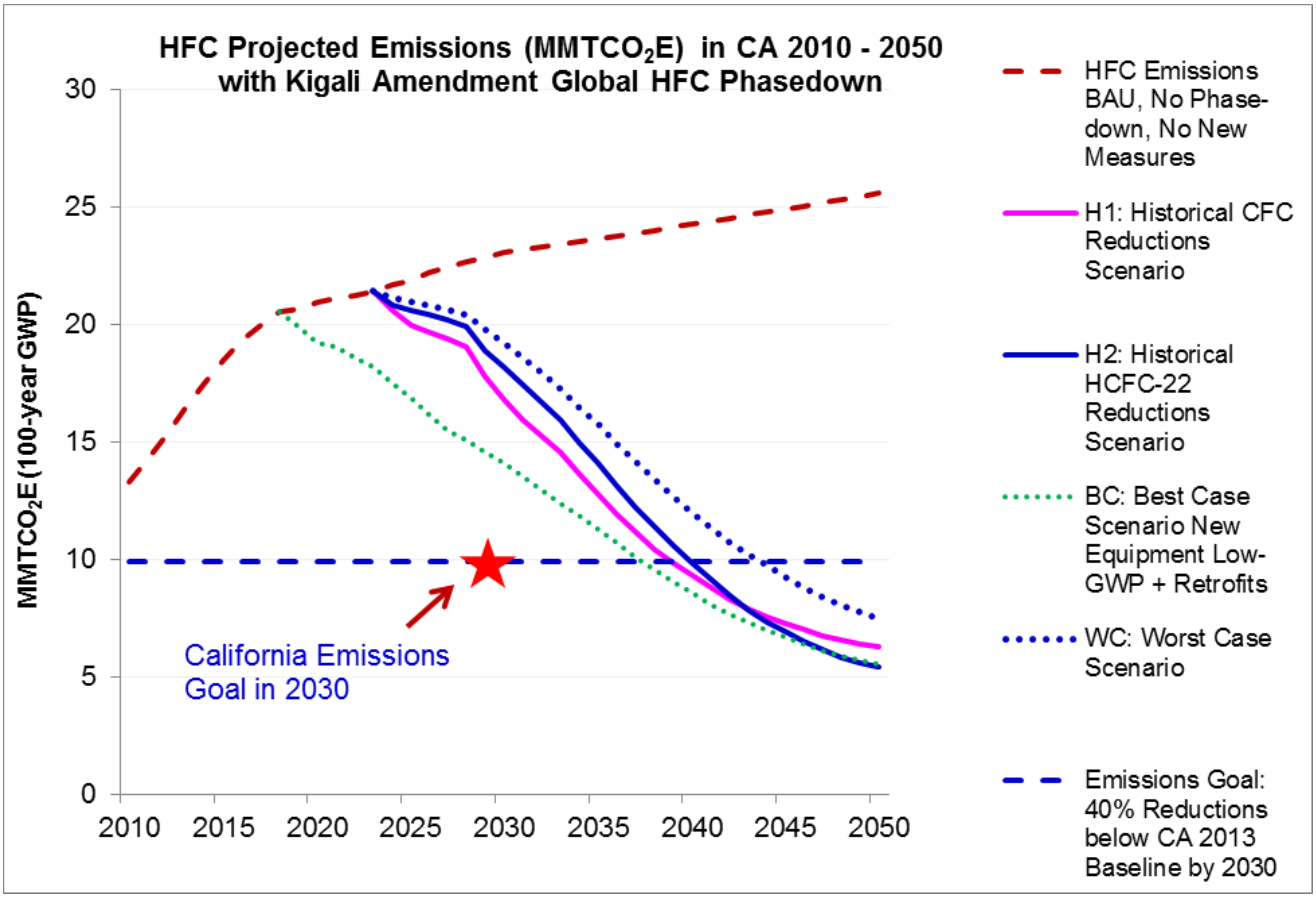
Table Notes:

1) In the stationary refrigeration and air-conditioning sectors, the refrigerants in the following sub-sectors are included under BAU emissions estimates because they are assumed to undergo no impact from the HFC phase-down due to existing U.S. EPA SNAP regulations (that will require them to use lower-GWP refrigerants ahead of HFC phase-down constraints): Residential refrigerator-freezers, refrigerated vending machines, self-contained (stand-alone) refrigeration units, and chillers. Due to existing U.S.

EPA SNAP rules, commercial refrigeration equipment used in retail food would not be impacted by the phase-down until 2024.

2) In the non-stationary sector, insulating foam and light-duty motor vehicle AC are assumed to become low-GWP ahead of HFC phase-down constraints due to U.S. EPA SNAP regulations, and these emissions reductions are included under BAU emissions estimates. Additionally, we assume that due to medical necessity, medical dose inhalers using HFC propellants will not change the propellants used today (HFC-134a and HFC-227ea). Fire suppressants and HFC used in semiconductor manufacturing are minimal (less than 0.5 percent HFC emissions) and are not included in the reductions model.

**Figure 9. HFC Projected Emissions in CA with Global HFC Phase-down, Worst Case Scenario; Slow Transition to Low-GWP.**



The following table shows the worst case scenario emissions as in the above graph, but expressed in tabular form (shown on following page to preserve continuity).

**Table 12. HFC Emissions in CA using hypothetical "Worst Case" reductions scenario.**

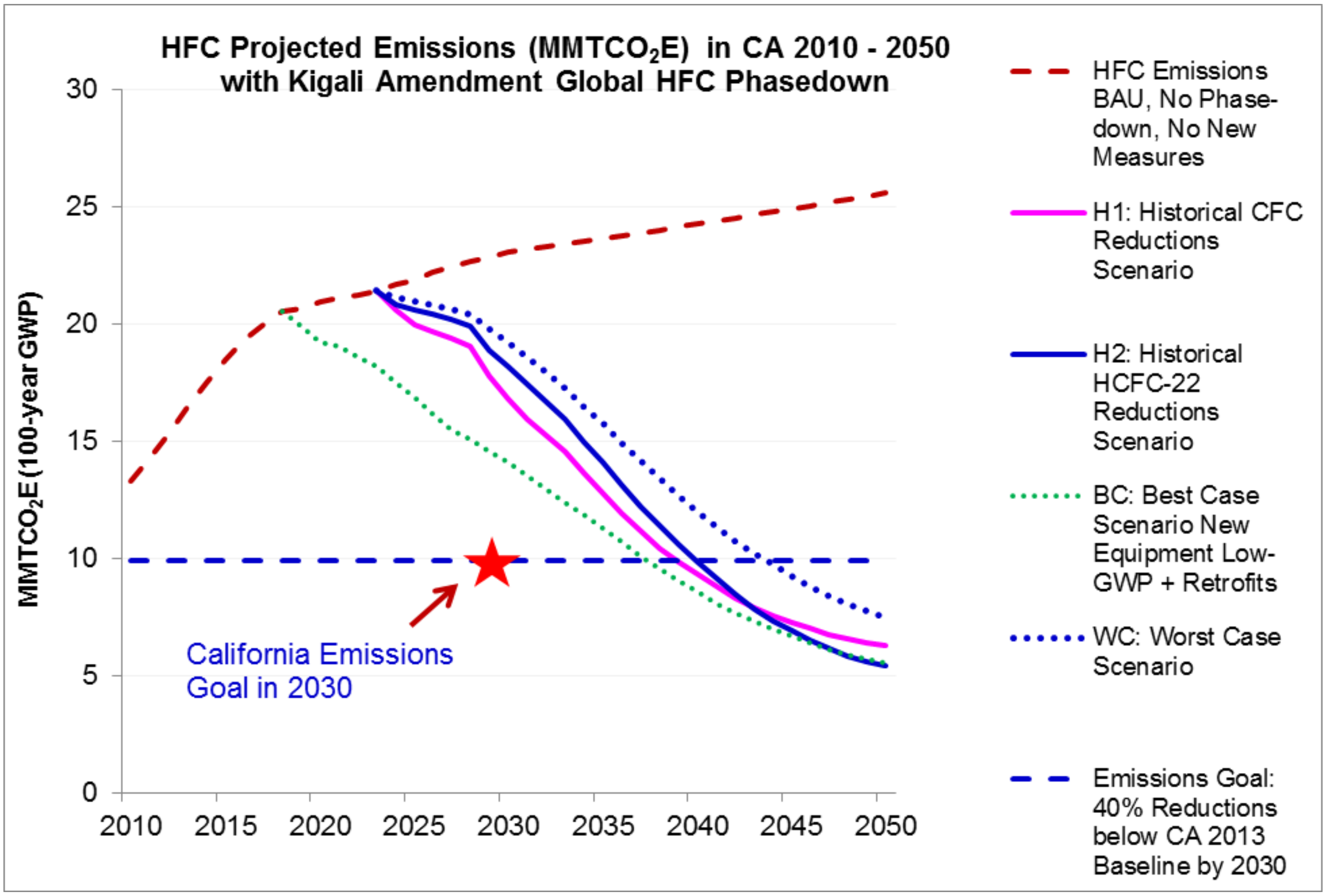
| Year | BAU Emissions in CA w/o Kigali | Absolute Annual Reductions from peak emissions ("reduction curve") | Annual reductions additional to BAU | Post-Kigali Emissions in CA |
|---|---|---|---|---|
| 2018 | 20.5 | 0% | 0 | 20.5 |
| 2019 | 20.6 | 0% | 0 | 20.6 |
| 2020 | 20.9 | 0% | 0 | 20.9 |
| 2021 | 21.1 | 0% | 0 | 21.1 |
| 2022 | 21.2 | 0% | 0 | 21.2 |
| 2023 | 21.4 | 0% | 0 | 21.4 |
| 2024 | 21.6 | 2.4% | 0.5 | 21.1 |
| 2025 | 21.9 | 2.0% | 0.9 | 20.9 |
| 2026 | 22.2 | 2.1% | 1.4 | 20.8 |
| 2027 | 22.4 | 2.1% | 1.8 | 20.6 |
| 2028 | 22.6 | 2.1% | 2.3 | 20.4 |
| 2029 | 22.8 | 4.0% | 3.1 | 19.7 |
| 2030 | 23.1 | 3.7% | 3.9 | 19.2 |
| 2031 | 23.2 | 3.7% | 4.6 | 18.5 |
| 2032 | 23.3 | 3.7% | 5.4 | 17.9 |
| 2033 | 23.4 | 3.6% | 6.2 | 17.2 |
| 2034 | 23.5 | 4.4% | 7.1 | 16.4 |
| 2035 | 23.6 | 4.1% | 7.9 | 15.7 |
| 2036 | 23.8 | 4.2% | 8.8 | 14.9 |
| 2037 | 23.9 | 4.3% | 9.7 | 14.1 |
| 2038 | 24.0 | 4.1% | 10.6 | 13.4 |
| 2039 | 24.1 | 4.0% | 11.4 | 12.7 |
| 2040 | 24.2 | 3.9% | 12.2 | 12.0 |
| 2041 | 24.4 | 3.6% | 13.0 | 11.4 |
| 2042 | 24.5 | 3.7% | 13.7 | 10.8 |
| 2043 | 24.6 | 3.2% | 14.4 | 10.2 |
| 2044 | 24.8 | 3.0% | 15.0 | 9.7 |
| 2045 | 24.9 | 3.0% | 15.7 | 9.2 |
| 2046 | 25.0 | 2.8% | 16.2 | 8.8 |
| 2047 | 25.2 | 2.6% | 16.8 | 8.4 |
| 2048 | 25.3 | 2.3% | 17.3 | 8.0 |
| 2049 | 25.4 | 2.1% | 17.7 | 7.7 |
| 2050 | 25.6 | 2.0% | 18.1 | 7.4 |

See Appendix E for an example of how the “worst case” scenario was applied to a specific emissions sector.

## 6. RESULTS - Projected HFC Emissions from the Kigali Amendment Phase-down

The projected HFC emissions in California as a result of potential actions taken in response to the HFC phase-down schedule has been modeled for four different scenarios, with results shown in the previous figure and repeated for section completeness in the following figure.

**Figure 10. Estimated HFC Emissions in CA as a result of the Kigali Amendment.**



Results indicate that the SB 1383 target of 40 percent HFC emissions reductions below 2013 levels by 2030 (indicated on the graph with a red star) will not be achieved through the Kigali Amendment alone until 2039-2040 at the earliest applying historical ODS reductions rates (Scenarios H1 and H2) and 2037-2038 applying the best case scenario (Scenario BC).

The worst-case scenario (Scenario WC) achieves 40 percent HFC emissions reductions in 2044. All yearly goal estimates have an uncertainty of plus/minus three years.

Relying upon the minimum actions needed to comply with the Kigali Amendment alone would not enable California to meet its HFC reduction goals until approximately one decade later than required.

Although the phase-down reduces production and consumption by 40 percent in 2024, and 70 percent in 2029, an equivalent reductions in emissions only occurs many years later. The significant time lag between consumption/production and emission reductions can be explained by the long lifetimes of equipment that emit high-GWP F-gases throughout their operating life (with average lifetimes of 12 to 20 years). The delay between a decrease in consumption/production and the intended emissions decrease has been called “the inertia of the installed base”.

High-GWP refrigerants are effectively “banked” in existing equipment and emission reductions lag according to the lifetime of that equipment. HFC emissions can only begin to decrease after the size of the high-GWP HFC bank diminishes. Meaningful emission reductions would not be expected until existing equipment using high-GWP HFCs are retired and replaced by lower-GWP equipment, or there is significant leak reduction or retrofits of existing systems.

For most end-use sectors, the average lifetime of equipment is about 15 years, which indicates that after the first significant phase-down step in 2024 is implemented, it may be another 15 years, or 2039 before the full effect of consequent HFC emissions reductions occurs (without additional measures addressing the GWP of the refrigerant used in the installed base of equipment). A rapid transition to low-GWP HFCs to avoid emission banking is critical for meeting the SB 1383 target.

### Summary Table: Emissions in MMTCO$_2$E as a result of the Kigali Amendment

The following table shows the estimated HFC emissions in California as a result of the reductions scenarios modeled. Only in the best case scenario does the first cap of 90 percent from 2019 through 2023 have any effect on emissions reductions, as the initial phase-down supply allowance is approximately equal to the projected BAU demand. (Table shown on following page to preserve continuity.)

### Table 13. HFC Emissions Estimates in California (MMTCO$_2$E, 100-year GWP) from Kigali Amendment HFC Phase-down

| Year | BAU Emissions | Scenario H1: Historical CFC Emissions | Scenario H2: Historical HCFC-22 Emissions | Scenario BC: Best Case, New Equipment Accelerated Low-GWP | Scenario WC: Worst Case, New Equip. Uses Highest Ave. GWP Avail. |
|---|---|---|---|---|---|
| 2018 | 20.5 | 20.5 | 20.5 | 20.5 | 20.5 |
| 2019 | 20.6 | 20.6 | 20.6 | 19.9 | 20.6 |
| 2020 | 20.9 | 20.9 | 20.9 | 19.2 | 20.9 |
| 2021 | 21.1 | 21.1 | 21.1 | 19.0 | 21.1 |
| 2022 | 21.2 | 21.2 | 21.2 | 18.6 | 21.2 |
| 2023 | 21.4 | 21.4 | 21.4 | 18.2 | 21.4 |
| 2024 | 21.6 | 20.6 | 20.8 | 17.5 | 21.1 |
| 2025 | 21.9 | 19.9 | 20.6 | 16.8 | 20.9 |
| 2026 | 22.2 | 19.6 | 20.4 | 16.2 | 20.8 |
| 2027 | 22.4 | 19.4 | 20.2 | 15.5 | 20.6 |
| 2028 | 22.6 | 19.0 | 19.9 | 15.1 | 20.4 |
| 2029 | 22.8 | 17.8 | 18.9 | 14.6 | 19.7 |
| 2030 | 23.1 | 16.8 | 18.2 | 14.1 | 19.2 |
| 2031 | 23.2 | 15.9 | 17.4 | 13.5 | 18.5 |
| 2032 | 23.3 | 15.3 | 16.7 | 12.9 | 17.9 |
| 2033 | 23.4 | 14.6 | 15.9 | 12.4 | 17.2 |
| 2034 | 23.5 | 13.6 | 15.0 | 11.8 | 16.4 |
| 2035 | 23.6 | 12.8 | 14.1 | 11.3 | 15.7 |
| 2036 | 23.8 | 11.9 | 13.1 | 10.7 | 14.9 |
| 2037 | 23.9 | 11.1 | 12.2 | 10.1 | 14.1 |
| 2038 | 24.0 | 10.4 | 11.4 | 9.5 | 13.4 |
| 2039 | 24.1 | 9.8 | 10.6 | 9.1 | 12.7 |
| 2040 | 24.2 | 9.3 | 9.9 | 8.5 | 12.0 |
| 2041 | 24.4 | 8.8 | 9.1 | 8.1 | 11.4 |
| 2042 | 24.5 | 8.3 | 8.5 | 7.6 | 10.8 |
| 2043 | 24.6 | 7.9 | 7.8 | 7.3 | 10.2 |
| 2044 | 24.8 | 7.5 | 7.3 | 7.0 | 9.7 |
| 2045 | 24.9 | 7.3 | 6.9 | 6.7 | 9.2 |
| 2046 | 25.0 | 7.0 | 6.5 | 6.4 | 8.8 |
| 2047 | 25.2 | 6.7 | 6.1 | 6.1 | 8.4 |
| 2048 | 25.3 | 6.5 | 5.8 | 5.9 | 8.0 |
| 2049 | 25.4 | 6.4 | 5.6 | 5.7 | 7.7 |
| 2050 | 25.6 | 6.3 | 5.4 | 5.5 | 7.4 |

Highlighted cells indicate the first year that the reductions scenario has achieved the 2030 HFC emissions reductions goal of 9.9 $MMTCO_2E$ emissions or less, which is 40 percent below the 2013 baseline HFC emissions of 16.5 $MMTCO_2E$.

An alternate way to view potential emissions reductions from the HFC phase-down is to apply the historical CFC and HCFC-22 emissions reductions curves data, and rather than use CO2-eq numbers, we use the relative emissions of HFCs compared to a baseline of 100 percent of emissions just prior to the first phase-down step in 2019. Note that due to the lag time between supply reductions and emissions reductions, the HFC supply can be just 30 percent of baseline, while the HFC emissions may still be up to 90 percent of baseline, as shown for year 2029.

**Table 14. Post-Kigali Emissions as Relative Percent of 2019 Emissions at Beginning of Phase-down**

| **Year** | **Production/ Consumption of HFCs compared to Cap** | **CFC Reduction Curve: Emissions of HFCs** (compared to 2019 phase-down start) | **HCFC-22 Reductions Curve: Emissions of HFCs** (compared to 2019 phase-down start) | **Notes** |
|---|---|---|---|---|
| 2019 | 90% | 100% | 100% | Phase-down begins |
| 2020 | 90% | 101% | 101% | Slightly increasing emissions despite 1st phase-down |
| 2021 | 90% | 102% | 102% | |
| 2022 | 90% | 103% | 103% | |
| 2023 | 90% | 104% | 104% | |
| 2024 | 60% | 98% | 102% | 2024 start of reductions using CFC curve; 2026 start of reductions using HCFC curve |
| 2025 | 60% | 95% | 101% | |
| 2026 | 60% | 94% | 99% | |
| 2027 | 60% | 92% | 98% | |
| 2028 | 60% | 91% | 96% | 10% emissions reductions nine years after 10% production cut |
| 2029 | 30% | 83% | 91% | |
| 2030 | 30% | 78% | 87% | |
| 2031 | 30% | 74% | 82% | |
| 2032 | 30% | 71% | 78% | |
| 2033 | 30% | 67% | 73% | |
| 2034 | 20% | 62% | 68% | |

| **Year** | **Production/ Consumption of HFCs compared to Cap** | **CFC Reduction Curve: Emissions of HFCs** (compared to 2019 phase-down start) | **HCFC-22 Reductions Curve: Emissions of HFCs** (compared to 2019 phase-down start) | **Notes** |
|---|---|---|---|---|
| 2035 | 20% | 58% | 63% | 40% emissions reductions 11 years after 40% production cut |
| 2036 | 15% | 53% | 58% | |
| 2037 | 15% | 50% | 53% | |
| 2038 | 15% | 46% | 49% | |
| 2039 | 15% | 43% | 44% | |
| 2040 | 15% | 41% | 40% | |
| 2041 | 15% | 38% | 37% | |
| 2042 | 15% | 36% | 34% | |
| 2043 | 15% | 34% | 32% | |
| 2044 | 15% | 32% | 30% | 70% emissions reductions 17 years after 70% production cut |
| 2045 | 15% | 30% | 28% | |
| 2046 | 15% | 28% | 26% | |
| 2047 | 15% | 26% | 26% | |
| 2048 | 15% | 24% | 24% | |
| 2049 | 15% | 22% | 22% | |
| 2050 | 15% | 21% | 21% | |

Note that due to the high initial cap of production and consumption of HFCs, the 15 percent consumption level from 2036 onward results in emissions in CA stabilizing just above 20 percent of the 2019 estimated HFC emissions. If the BAU in 2019 had been greater because of no CARB or U.S. EPA regulations, then the production/consumption cap and demand would have been in closer alignment, and emissions would have been eventually reduced to about 15 percent of their peak "no regulation" levels. Relative reductions aside, the actual emissions of HFCs will be reduced to levels that are at least 85 percent lower than what they would have been without the Kigali Amendment.

## 7. CONCLUSIONS

The impact of the global HFC phase-down ("Kigali Amendment" or "Kigali Agreement") on the HFC emissions in California were modeled using best estimates of actual HFC emissions in California currently, under BAU conditions through 2050, and applying four different reductions scenarios to the Kigali phase-down schedule:

1) The historical rate of reductions from the CFC phase-out (Scenario H1).

2) The historical and ongoing rate of reductions from the HCFC-22 phase-down and eventual total phase-out January 1, 2020 (Scenario H2).

3) A "best case" scenario where new equipment transitions to low-GWP alternatives as soon as feasible, and existing equipment using very-high GWP refrigerants ≥ 2500 GWP value retrofit to refrigerants with a GWP of 1500 (Scenario BC).

4) A "worst case" scenario where the HFC phase-down only affects new equipment, and existing equipment continues to use the high-GWP HFCs they were originally designed to use (Scenario WC).

Applying the historical ODS reductions trends to the HFC phase-out, CARB modeling indicates that it is likely that the Kigali Amendment HFC phase-down impact on California will only achieve 37 to 48 percent of reductions required by SB 1383 by 2030, for an average of 42 percent (± 15 percent) of the goal achieved. The California HFC emissions reduction goal with the target year of 2030 would not be achieved until the years 2039-2040 (± three years).

A "best case" scenario would achieve the emissions reductions goal by 2038, while a "worst case" scenario would delay the reductions goal until 2044 (± three years).

Although the "best case" scenario (shown in Figure 10) does not result in significantly lower *annual* emissions by 2030, compared to the historical ODS reductions scenarios, it does result in greater *initial* emissions reductions and *cumulative* emissions reductions by 2030.

The best case scenario achieves an additional 37 $MMTCO_2E$ cumulative reductions in California by 2030 from an early transition to low-GWP refrigeration and AC equipment, (The reductions of 37 $MMTCO_2E$ are equal to all the HFC emissions in California for years 2015 and 2016 combined.) However, the best case scenario is not very likely without additional HFC prohibitions to complement and strengthen the phase-out.

The following table shows the different reductions impacts by year 2030 from each of the four reductions scenarios modeled. None of the phase-down reductions scenarios modeled result in reducing HFC emissions sufficiently to achieve California's HFC emissions reductions goals by the year 2030. (Table shown on following page to preserve table continuity.)

**Table 15. Impact of the Kigali Amendment: Estimated HFC Emissions in CA in 2030 as Modeled by Four Scenarios, and Percent of Reductions Goal achieved by Each Scenario.**

| HFC Phase-down Scenario Modeled | Estimated Emissions in CA 2030 ($MMTCO_2E$) | Percent of Emissions Goal (9.9 $MMTCO_2E$) Achieved by 2030[a] (± 15%) | Estimated Year Emissions Goal Achieved (± 3 Years) |
|---|---|---|---|
| BAU: Business as Usual (no Phase-down) | 23.1 | 0% | N/A |
| BC: Best Case | 14.1 | 68% | 2038 |
| H1: ODS Historical Reductions of CFCs | 16.8 | 48% | 2039 |
| H2: ODS Historical Reductions of HCFC-22 | 18.2 | 37% | 2040 |
| WC: Worst Case | 19.2 | 30% | 2044 |

Table Notes: a) The emissions goal is to reduce annual emissions of HFCs 40 percent below 2013 levels by 2030, equal to reducing BAU emissions in 2030 of 23.1 $MMTCO_2E$ to 9.9 $MMTCO_2E$. To achieve 100 percent of the reductions goal, emissions must decrease 13.2 $MMTCO_2E$ annually below BAU.

The assumptions used in this model may underestimate future emissions of HFCs under the Kigali phase-down schedule. For example, because only allocated HFCs are assumed to represent all available supply beginning in 2024, the effects of stockpiling and illegal sources of refrigerants are ignored in all scenarios except the “worst case” scenario, potentially a very substantial undercounting.

Without HFC emissions reduction measures in addition to the HFC consumption phase-down, California will be unable to meet the 2030 HFC reduction goals mandated by SB 1383. The Short-Lived Climate Pollutant Reduction Strategy (April 2017) proposes several HFC emissions reductions measures that will be considered for rule-making (CARB, 2017b).

Although the subject of separate research apart from this methodology, preliminary CARB analysis indicates that California’s HFC emissions reductions goal of annual emissions 40 percent below 2013 levels by 2030 is likely to be met if the all of the following measures are enacted:

1) The Kigali Amendment HFC phase-down schedule and production/consumption limits are followed by the United States.

2) U.S. EPA SNAP Rules 20 and 21 (prohibiting certain high-GWP HFCs in new and retrofit refrigeration equipment, chillers, MVAC, and insulating foam) are kept in place and enforced.

3) New refrigeration and AC equipment is designed and manufactured to use refrigerants with the lowest feasible GWP. Voluntary or regulatory measures to prohibit new high-GWP equipment and require low-GWP equipment must be enacted within five years.

4) Existing equipment using high-GWP refrigerants that require replacement refrigerant must retrofit to refrigerants with significantly lower GWPs (50 percent or less of the GWP value than the original refrigerant).

5) Accidental or intentional venting of refrigerant at equipment end-of-life must not increase from today's levels, and ideally will decrease.

## APPENDICES

The following appendices are included in the section:

**A. Summary of Methodology to Estimate BAU HFC Emissions in California**

**B. Timeline of Class I ODS phase-out, Historical and Projected Refrigerant Trends in the U.S.; and CFC "Reductions Curve" applied to the HFC Phase-down Schedule**

**C. HFC End-Use Sectors with no Likely Reductions from HFC Phase-down**

**D. Impact on Emissions from Servicing Demand and Retrofits**

**E. Example of "Worst Case" Emissions Reductions Scenario**

**F. Further Background on the Kigali Baseline**

**G: Additionality of HFC Emissions Reductions in California and Potential Leakage of Emissions**

**H: Supply versus Demand: Initial HFC Supply Cap is Greater than Business-as-Usual (BAU) Demand of HFCs**

**I. Acronym List and Glossary**

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## Appendix A: Summary of Methodology to Estimate BAU HFC Emissions in California.

CARB identified eleven (11) broad categories of F-gas emissions sectors, which were further segregated into an additional 36 specific emission sub-sectors, as listed in the following Table A1.

**Table A1. F-gas Emission Sectors and Sub-sectors**

| Emission Sector of F-gas | Sub-sector Description |
|---|---|
| Aerosol propellants (MDI) | Metered Dose Inhalers (MDI) |
| Aerosol propellants (non-MDI) | Consumer Product and Commercial/Industrial Aerosols |
| Commercial Refrigeration and AC Large (systems > 50-lbs.) | Centralized system ≥2,000 lbs. |
| | Centralized system 200-<2,000 lbs. |
| | Centrifugal chiller ≥2,000 lbs. |
| | Centrifugal chiller 200-<2,000 lbs. |
| | Chiller - packaged 200-<2,000 lbs. |
| | Cold storage ≥2,000 lbs. |
| | Cold storage 200-<2,000 lbs. |
| | Process cooling ≥2,000 lbs. |
| | Refrigerated condensing units 50-< 200 lbs. |
| | Unitary AC 50-<200 lbs. |
| Commercial Refrigeration and AC Small (Systems ≤ 50-lbs.) | Refrigerated condensing units ≤ 50 lbs. |
| | Stand-alone (self-contained) refrigerated units |
| | Refrigerated vending machines |
| | Unitary AC (≤ 50-lbs.) |
| | Window AC units (commercial) |
| Fire Protection | Fire Suppressants |
| Foam, Insulating | Foam (appliance, building, refrigeration equipment, transport, marine buoyancy) |
| Industrial | Industrial Solvents |
| | Semiconductor Manufacturing |
| | Sulfur hexafluoride uses |
| Medical | Medical Sterilants |

| **Emission Sector of F-gas** | **Sub-sector Description** |
|---|---|
| Mobile and Transport | Light Duty (LD) Vehicle AC |
| | Heavy Duty (HD) Vehicle (non-Bus) AC |
| | Bus AC |
| | Off-road Heavy Duty Vehicle |
| | Transport Refrigerated Units (TRUs) including rail cars |
| | Refrigerated Shipping Containers |
| | Ships (Marine Vessels) |
| | Passenger Train AC |
| | Aircraft AC |
| Pesticide | Sulfuryl fluoride uses |
| Residential | Residential refrigerator-freezer (appliance) |
| | Residential AC unitary |
| | Window AC units (residential) |

After F-gas sectors were identified as distinct emission sectors with their own emission profile, the specific F-gases each sector used were identified. The following table shows the F-gas compounds and blends of F-gases used in the emissions methodology.

**Table A2: F-gas compounds, blends of F-gases, and their GWP values.**

| **F-gas Compound (chemical)** | **IPCC AR4 GWP 100-yr [1]** | **IPCC AR4 GWP 20-yr [1]** |
|---|---:|---:|
| CFC-11 | 4750 | 6730 |
| CFC-12 | 10900 | 11000 |
| CFC-113 | 6130 | 6540 |
| CFC-114 | 10000 | 8040 |
| CFC-115 | 7370 | 5310 |
| Halon 1211 | 1890 | 4750 |
| Halon 1301 | 7140 | 8480 |
| HCFC-22 | 1810 | 5160 |
| HCFC-123 | 77 | 273 |
| HCFC-124 | 609 | 2070 |
| HCFC-141b | 725 | 2250 |

| **F-gas Blend** | **F-gas Group** | **IPCC AR4 GWP 100-yr** | **IPCC AR4 GWP 20-yr** |
|---|---|---:|---:|
| R-500 | CFC | 8077 | 8232 |
| R-502 | CFC | 4657 | 5237 |
| R-401A | HCFC | 1182 | 3495 |
| R-401B | HCFC | 1288 | 3775 |
| R-402A | HCFC | 2788 | 5771 |
| R-402B | HCFC | 2416 | 5509 |
| R-403B | HCFC | 4458 | 5351 |
| R-406A | HCFC | 1943 | 5089 |
| R-408A | HCFC | 3152 | 5579 |
| R-409A | HCFC | 1585 | 4437 |
| R-414A | HCFC | 1478 | 4317 |

| F-gas Compound (chemical) | IPCC AR4 GWP 100-yr [1] | IPCC AR4 GWP 20-yr [1] | | F-gas Blend | F-gas Group | IPCC AR4 GWP 100-yr | IPCC AR4 GWP 20-yr |
|---|---|---|---|---|---|---|---|
| HCFC-142b | 2310 | 5490 | | R-414B | HCFC | 1362 | 3899 |
| HCFC-225 ca/cb | 359 | 1230 | | R-416A | HCFC | 1084 | 3862 |
| HFC-23 | 14800 | 12000 | | R-404A | HFC | 3922 | 6010 |
| HFC-32 | 675 | 2330 | | R-407A | HFC | 2107 | 4538 |
| HFC-43-10mee | 1640 | 4140 | | R-407B | HFC | 2245 | 4494 |
| HFC-125 | 3500 | 6350 | | R-407C | HFC | 1774 | 4115 |
| HFC-134a | 1430 | 3830 | | R-407F | HFC | 1825 | 4136 |
| HFC-143a | 4470 | 5890 | | R-410A | HFC | 2088 | 4340 |
| HFC-152a | 124 | 437 | | R-413A | HFC | 2053 | 3938 |
| HFC-227ea | 3220 | 5310 | | R-417A | HFC | 2346 | 4874 |
| HFC-236fa | 9810 | 8100 | | R-421A | HFC | 2631 | 5294 |
| HFC-245fa | 1030 | 3380 | | R-422A | HFC | 3143 | 5844 |
| HFC-365mfc | 794 | 2520 | | R-422B | HFC | 2526 | 5101 |
| PFC-14 | 7390 | 5210 | | R-422C | HFC | 3085 | 5782 |
| PFC-116 | 12200 | 8630 | | R-422D | HFC | 2729 | 5340 |
| PFC-218 | 8830 | 6310 | | R-423A | HFC | 2280 | 4533 |
| PFC-318 | 10300 | 7310 | | R-424A | HFC | 2440 | 5007 |
| $NF_3$ | 17200 | 12300 | | R-427A | HFC | 1912 | 4441 |
| $SF_6$ | 22800 | 16300 | | R-437A | HFC | 1800 | 4245 |
| $SO_2F_2$ | 4090 | 6840 | | R-438A | HFC | 2265 | 4659 |
| HFO-1234yf[2] | < 10 | < 10 | | R-507 | HFC | 3985 | 6120 |
| HFO-1233zd | < 10 | < 10 | | R-508B | HFC | 13396 | 10180 |
| HFO-1234ze | < 10 | < 10 | | PFC/PFPEs blends (not otherwise specified) | PFC | 9300 | 6600 |

Key to table color code:

Pink: CFCs and brominated halons that are Class I ODS (strongly ozone-depleting).
Blue: HCFCs that are Class II ODS (weakly ozone depleting; 89 to 99 percent less ozone-depleting than Class I ODS).
Purple: PFCs, $NF_3$, and $SF_6$, which are non-ozone depleting, and non-HFC F-gases with very high GWP values, and are included in the Kyoto Protocol to reduce greenhouse gases ($NF_3$ was added to the revised Kyoto Protocol)
Orange: $SO_2F_2$ (sulfuryl fluoride) is non-ozone depleting, non-HFC, and a high-GWP F-gas not included in the Kyoto Protocol.
Green: HFOs are the newest synthetic fluorinated compounds that are non-ozone depleting and low-GWP.
White/Clear (no shading): The most common HFC compounds and blends. Not a complete list of all HFCs, but the listed HFCs contributes more than 99 percent of all GHG emissions from HFCs.

Table notes:
1) GWP values are from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), 2007; “Climate Change 2007: Working Group I: The Physical Science Basis” chapter 2, “Changes in Atmospheric Constituents and in Radiative Forcing”, section 2.10.2 “Direct Global Warming Potentials”.

2) GWP values for HFOs are listed as 1, or < 1, in the IPCC Fifth Assessment Report (AR5), 2013; “Working Group I: The Physical Science Basis” chapter 8, “Anthropogenic and Radiative Forcing”, Table 8-A1 “Lifetimes, Radiative Efficiencies and Metric Values”. Comments received on the draft version of this methodology indicated that the GWP values for HFOs were not considered settled science, and the GWPs may be greater than one. Accordingly, HFOs have been assigned to a GWP of “< 10” in this methodology. Greenhouse gas emissions impacts from fluorinated gases with a GWP value between 1 and 10 are negligible when compared to total GHG emissions of all F-gases.

To estimate GHG emissions from each sector, the mass of emissions in pounds were calculated using the following:

*Emissions (lbs.) = [number of units (equipment) in use * average F-gas charge (lbs.)/unit * average annual leak or loss rate]*

*+ [number of units reaching EOL * average F-gas charge at EOL (lbs.)/unit * average loss rate at EOL]*

The emissions input factors are shown on Table A3, (on following page to preserve table continuity).

## Table A3: Input Factors for Emission Calculations, Refrigeration and AC (stationary, transport refrigerated units, and refrigerated shipping containers)

| Equipment Type or Emissions sub-sector | Units in CA 2016 | Ave. Charge (amount) of F-gas in lbs. | Ave. Annual Leak (loss) Rate | Annual Loss in lbs. (units* charge* loss rate) | EOL units in CA 2016 | Ave. Charge (amount) in lbs. at EOL | Ave. EOL Loss Rate | EOL Loss in lbs. (units* charge* loss rate) | total loss in lbs. (annual + EOL) |
|---|---|---|---|---|---|---|---|---|---|
| Refrigeration Large Centralized System ≥ 907.2 kg (2,000 lbs.) | 850 | 3,635 | 18.0% | 556,155 | 45 | 2,871 | 20% | 25,839 | 581,994 |
| Refrigeration Medium Centralized System 90.7-< 907.2 kg (200-< 2,000 lbs.) | 24,100 | 704 | 18.0% | 3,053,952 | 1,285 | 577 | 20% | 148,289 | 3,202,241 |
| AC Large Centrifugal Chiller ≥ 907.2 kg (2,000 lbs.) | 5,240 | 3,978 | 2.3% | 479,429 | 210 | 3,887 | 20% | 163,254 | 642,683 |
| AC Medium Centrifugal Chiller 90.7-< 907.2 kg (200-< 2,000 lbs.) | 1,655 | 1,007 | 1.4% | 23,332 | 65 | 993 | 20% | 12,909 | 36,241 |
| AC Chiller - Packaged 90.7-< 907.2 kg (200-< 2,000 lbs.) | 10,345 | 526 | 6.9% | 375,461 | 415 | 490 | 20% | 40,670 | 416,131 |
| Refrigeration Large Cold Storage ≥ 907.2 kg (2,000 lbs.) | 150 | 7,929 | 15.9% | 189,107 | 6 | 5,788 | 20% | 6,946 | 196,052 |
| Refrigeration Medium Cold Storage 90.7-< 907.2 kg (200-< 2,000 lbs.) | 425 | 494 | 18.0% | 37,791 | 20 | 316 | 20% | 1,264 | 39,055 |
| Refrigeration Process Cooling ≥ 907.2 kg (2,000 lbs.) | 107 | 5,242 | 10.0% | 56,089 | 4 | 4,718 | 20% | 3,774 | 59,864 |
| Refrigerated Condensing Units 22.7-≤ 90.7 kg (50-≤ 200 lbs.) | 78,850 | 122 | 15.0% | 1,442,955 | 3,150 | 122 | 20% | 76,860 | 1,519,815 |
| Unitary AC 22.7-≤ 90.7 kg (50-≤ 200 lbs.) | 89,400 | 100 | 11.3% | 1,010,220 | 4,000 | 89 | 20% | 71,200 | 1,081,420 |
| Refrigerated Condensing Units ≤ 22.7 kg (50-lbs. or less) | 319,300 | 31.4 | 15.0% | 1,503,903 | 12,800 | 27 | 34% | 117,504 | 1,621,407 |

| **Equipment Type or Emissions sub-sector** | **Units in CA 2016** | **Ave. Charge (amount) of F-gas in lbs.** | **Ave. Annual Leak (loss) Rate** | **Annual Loss in lbs. (units* charge* loss rate)** | **EOL units in CA 2016** | **Ave. Charge (amount) in lbs. at EOL** | **Ave. EOL Loss Rate** | **EOL Loss in lbs. (units* charge* loss rate)** | **total loss in lbs. (annual + EOL)** |
|---|---|---|---|---|---|---|---|---|---|
| Stand-alone (self-contained) refrigeration equipment | 696,500 | 1.1 | 0.2% | 1,532 | 27,900 | 1.1 | 98% | 29,983 | 30,515 |
| Refrigerated vending machines | 532,300 | 0.66 | 0.2% | 703 | 28,400 | 0.66 | 98% | 17,534 | 18,237 |
| Unitary A/C ≤ 22.7 kg (50-lbs. or less) (central) | 2,746,000 | 15.1 | 10.0% | 4,146,460 | 145,500 | 12.1 | 56% | 985,908 | 5,132,368 |
| Commercial AC (window unit) | 651,000 | 1.54 | 2.0% | 20,051 | 43,400 | 1.17 | 98% | 55,292 | 75,343 |
| Residential Appliance (refrigerator-freezer) | 17,984,000 | 0.34 | 1.0% | 61,146 | 1,028,000 | 0.29 | 77% | 229,552 | 290,698 |
| Residential A/C (central) | 9,500,000 | 7.5 | 6.3% | 4,448,750 | 392,000 | 6.1 | 80% | 1,913,000 | 6,391,750 |
| Residential A/C (window unit) | 5,170,000 | 1.54 | 2.0% | 159,240 | 430,300 | 1.17 | 98% | 548,202 | 707,442 |
| Transport Refrigerated Units (TRUs) | 58,500 | 20.7 | 18.3% | 221,604 | 4,650 | 17.4 | 15% | 12,137 | 233,740 |
| Refrigerated Shipping Containers | 54,500 | 33.1 | 5.0% | 90,198 | 16,300 | 33.1 | 19% | 102,511 | 192,708 |

To convert the F-gas emissions into GHG emissions by carbon-dioxide equivalents, an F-gas profile was developed for each emissions sector based on the type of F-gas used in the equipment for a given year of manufacture. U.S. EPA Vintaging Model assumptions were used to develop F-gas profiles (Godwin, et al., 2003; and U.S. EPA, 2008).

The formula used to convert pounds emissions of an F-gas to metric tonnes $CO_2$-Equivalents ($MTCO_2E$) is as follows:

F-gas lbs. * GWP of F-gas * 0.0004535924 metric tonnes/pound = $MTCO_2E$

F-gas Sectors using Complex Calculation Inputs

Emissions estimates for the remaining F-gas sectors (not shown previously in Table A3) are categorized as “complex” because no simple emissions estimates formula exists to calculate emissions. For example, AC refrigerant emissions from mobile vehicles employs two sophisticated vehicle emissions models known as the CARB EMissions FACtor model (EMFAC 2011), and the OFFROAD (2007) model. Refrigerant emissions from marine vessels represented a particular challenge because there were five different ship types analyzed, and also due to the lack of specific information on the number of days the various types of ships spent in California waters, which were not known with certainty for all types of ships. Insulating foam emissions were estimated as a result of a three-year study by Caleb Management Services for CARB, where the foam emissions were estimated for 19 distinct categories of insulating foam.

**Table A4. F-gas Emissions Sectors, “complex” emissions sectors.**

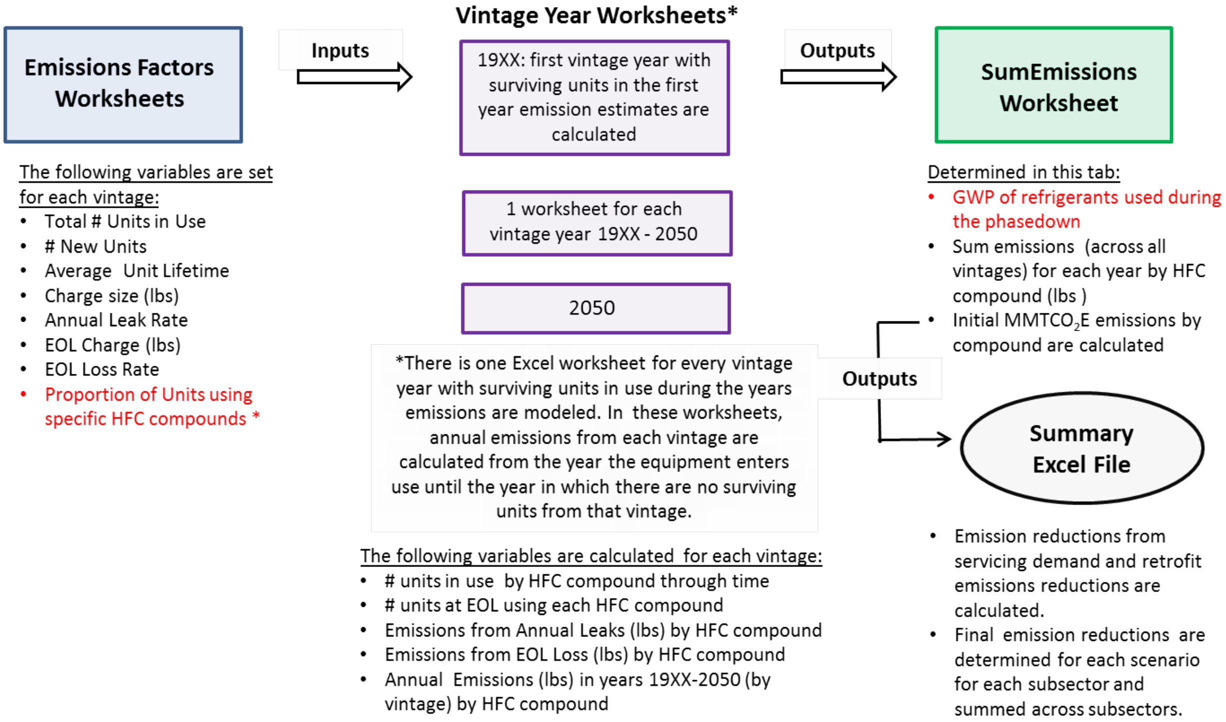
| **F-gas Emissions Sector** | **Estimated Emissions (lbs.) in CA, 2016** | **Notes** |
|---|---:|---|
| Aircraft AC | < 100 lbs. | Negligible source of F-gas. |
| Consumer product (and commercial/industrial) aerosol propellants | 5,116,000 | HFC-152a with the “relatively low” GWP of 124 comprises 87% of emissions. |
| Fire suppressants | 39,000 | Decreasing source of HFCs. |
| Insulating foam | 5,610,000 | Approximately 65% emissions are ODS due to long life span and large installed base (banks) of F-gases. U.S. EPA SNAP Program requires foam expansion agents to be low-GWP by 2021. |
| Medical sterilants | None | Stopped using F-gases in 2014. |
| Metered Dose Inhaler (MDI) aerosol propellant | 210,000 | Also known as medical dose inhalers (for asthma). |
| Mobile vehicle AC | 7,485,000 | Four sub-categories: Light duty (76%), heavy-duty non-bus (17%), bus (3%), and off-road (4%). U.S. EPA SNAP Program requires refrigerants used in light-duty MVAC to be low-GWP by Model Year 2021. |

| F-gas Emissions Sector | Estimated Emissions (lbs.) in CA, 2016 | Notes |
|---|---|---|
| Rail (Train) AC | 9,000 | Relatively negligible, does not include rail refrigeration which is part of refrigerated shipping containers. |
| Semiconductor manufacturing | 98,000 | Approximately 88% of emissions are from very-high GWP PFCs and $NF_3$ ($SF_6$ is reported as a separate category). |
| Ships (marine vessels) | 64,000 | Refrigeration and AC. |
| Solvents (non-semiconductor) | 575,000 | More than 140,000 pounds/year of illegally imported CFC-113 may still be used in the clandestine manufacturing of methamphetamines (OEHHA, 2011). |
| Sulfur hexafluoride ($SF_6$) | 26,000 | Used in semiconductor manufacturing and electrical switchgear. |
| Sulfuryl fluoride ($SO_2F_2$) | 2,835,000 | Used primarily as a pesticide fumigant for drywood termites. Replaced methyl bromide, an ODS. No adequate substitutes that are both non-ODS and low-GWP have been found yet for most insect fumigant applications. |

Example of BAU emissions estimates:

For each sector, an emission spreadsheet is developed (including “complex” emissions sectors). The spreadsheet format is generally the same for each sector and the flow of inputs to outputs within a sector-specific spreadsheet is detailed below in Figure A1.

**Figure A1. Excel Spreadsheet Model Framework.**



The following variables are set for each vintage:

- Total # Units in Use
- # New Units
- Average Unit Lifetime
- Charge size (lbs)
- Annual Leak Rate
- EOL Charge (lbs)
- EOL Loss Rate
- Proportion of Units using specific HFC compounds *

*There is one Excel worksheet for every vintage year with surviving units in use during the years emissions are modeled. In these worksheets, annual emissions from each vintage are calculated from the year the equipment enters use until the year in which there are no surviving units from that vintage.

The following variables are calculated for each vintage:

- # units in use by HFC compound through time
- # units at EOL using each HFC compound
- Emissions from Annual Leaks (lbs) by HFC compound
- Emissions from EOL Loss (lbs) by HFC compound
- Annual Emissions (lbs) in years 19XX-2050 (by vintage) by HFC compound

Determined in this tab:

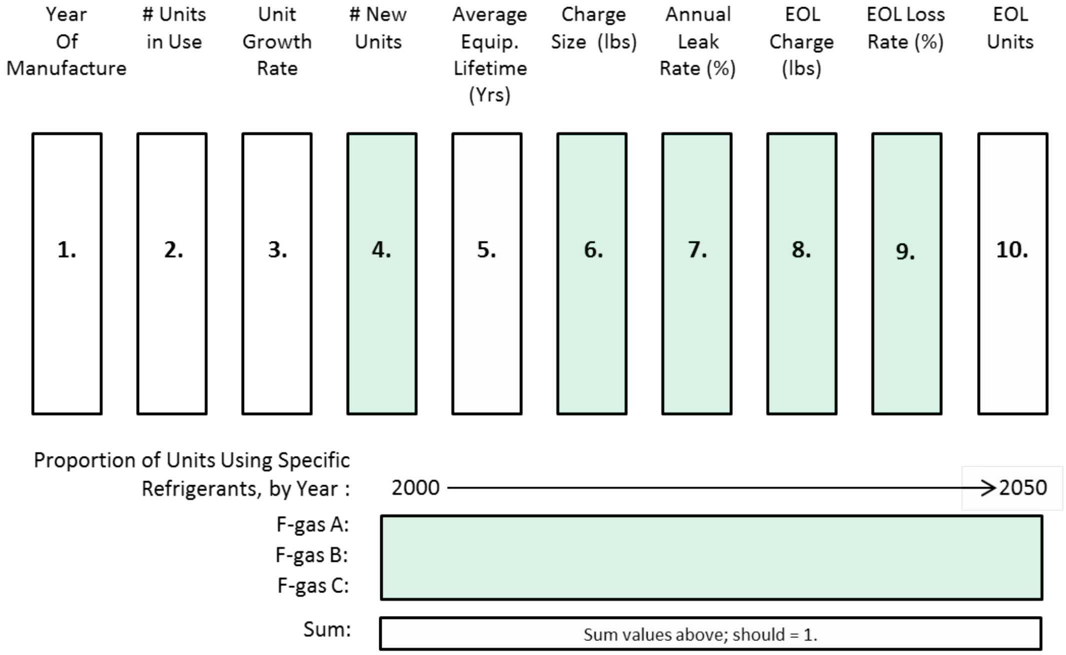
- GWP of refrigerants used during the phasedown
- Sum emissions (across all vintages) for each year by HFC compound (lbs )
- Initial $MMTCO_2E$ emissions by compound are calculated

- Emission reductions from servicing demand and retrofit emissions reductions are calculated.
- Final emission reductions are determined for each scenario for each subsector and summed across subsectors.

(Each box represents an Excel worksheet, and a circle indicates a separate Excel file. Red text indicates where changes are made in the excel file to model BAU and Kigali emission reduction scenarios.)

As in Figure A1 above, inputs such as number of units, leak rates and types of refrigerant used are set in an “emission factors” worksheet (Figure A2). The annual emissions from each vintage of equipment are calculated in a separate worksheet for each vintage year (Figure A3) using inputs from the “emission factors” worksheet. The annual emissions from all vintages of equipment in use during a given year are then aggregated in a “SumEmissions” worksheet (Figure A4). Emissions are aggregated across sectors in a separate summary spreadsheet.

## Figure A2. Emission Factors Worksheet.



1. **Year of Manufacture.** The year of the vintage.

2. **# Units in Use.** The number of units in use an input for 2010. All other years use the unit growth ratio to derive the number of units in use for that year.

3. **Unit Growth Rate.** Assumed to equal to California's growth rate.

4. **# New Units.** In 2010, the number of new units is assumed to be the total number of units in use divided by the average equipment lifetime (**5.**). For all other years, the number of new units changes according to the unit growth rate (**3.**).

5. **# Average Equipment Lifetime (Yrs)**. Assumed to be the same for all vintages within the same subsector.

6. **Charge Size (lbs).** Assumed to be the same for all vintages within the same subsector.

7. **Annual Leak Rate (%).** Assumed to decrease over time until a certain value is reached.

8. **EOL Charge (lbs).** Assumed to be the same for all vintages within the same subsector.

9. **EOL Loss Rate (%).** Assumed to decrease over time until a certain value is reached.

10. **EOL Units.** Number of units estimated to be at EOL.

11. **Proportion of Units Using Specific Refrigerants, by Year.** This is where the proportion of F-gases used is set. These values are used in the Vintage Year Tabs to calculated the lbs of each F-gas emitted.

**Key**

🟩 These values are inputs (linked) to the Vintage Year worksheets.

Figure Note:
1) Item 7 - Leak rates are updated annually based on data reported to RMP. For future emissions projections, annual leak rates are assumed to decrease over time through 2030 until the leak rate is no more than ten percent annually for larger equipment, and five percent annually for smaller equipment.
2) Retrofits to higher or lower-GWP refrigerants are not modeled in the basic emissions factors. Retrofit estimates are modeled separately after the basic emissions have been modeled and estimated.

**Figure A3. Vintage Year Worksheet.**

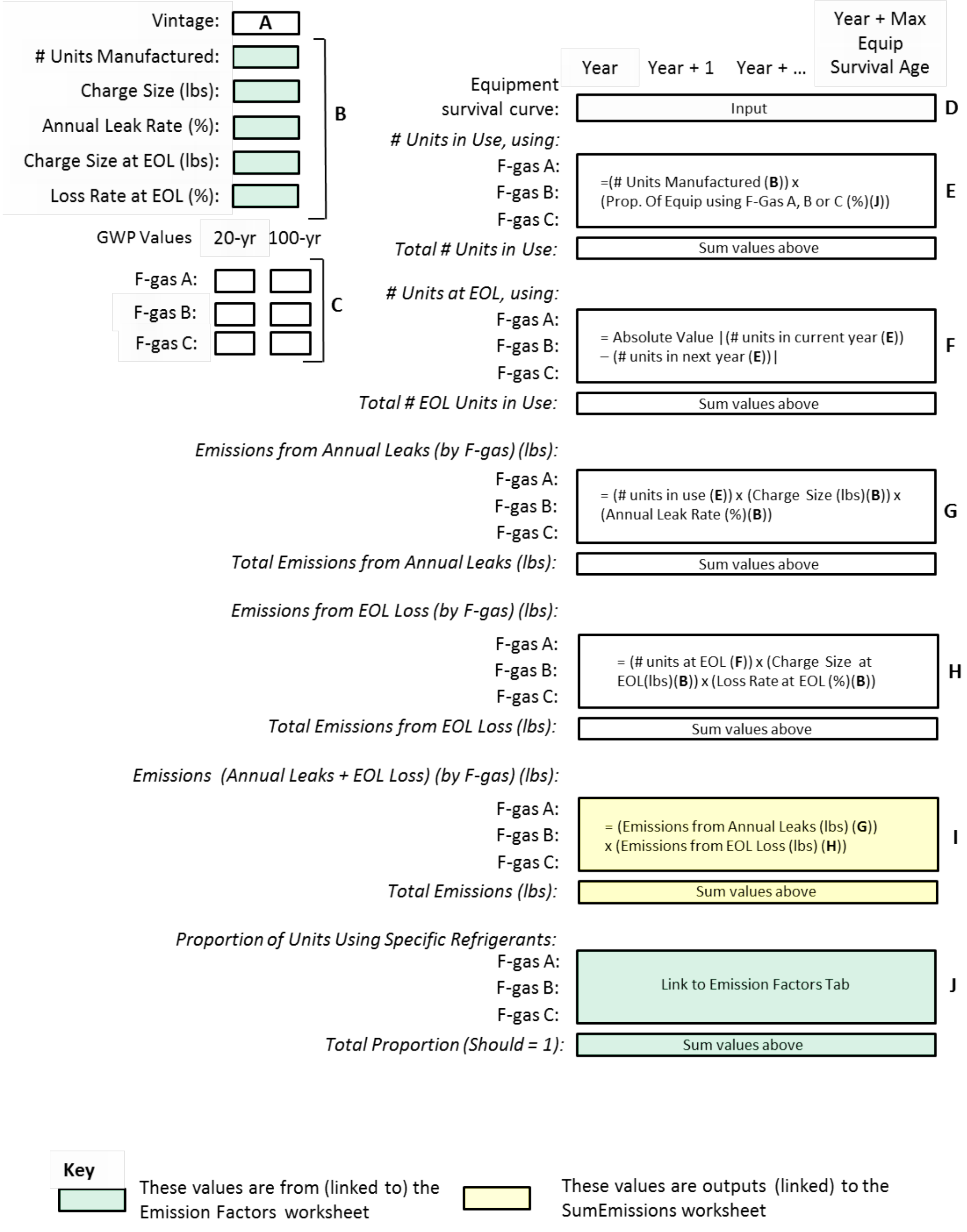
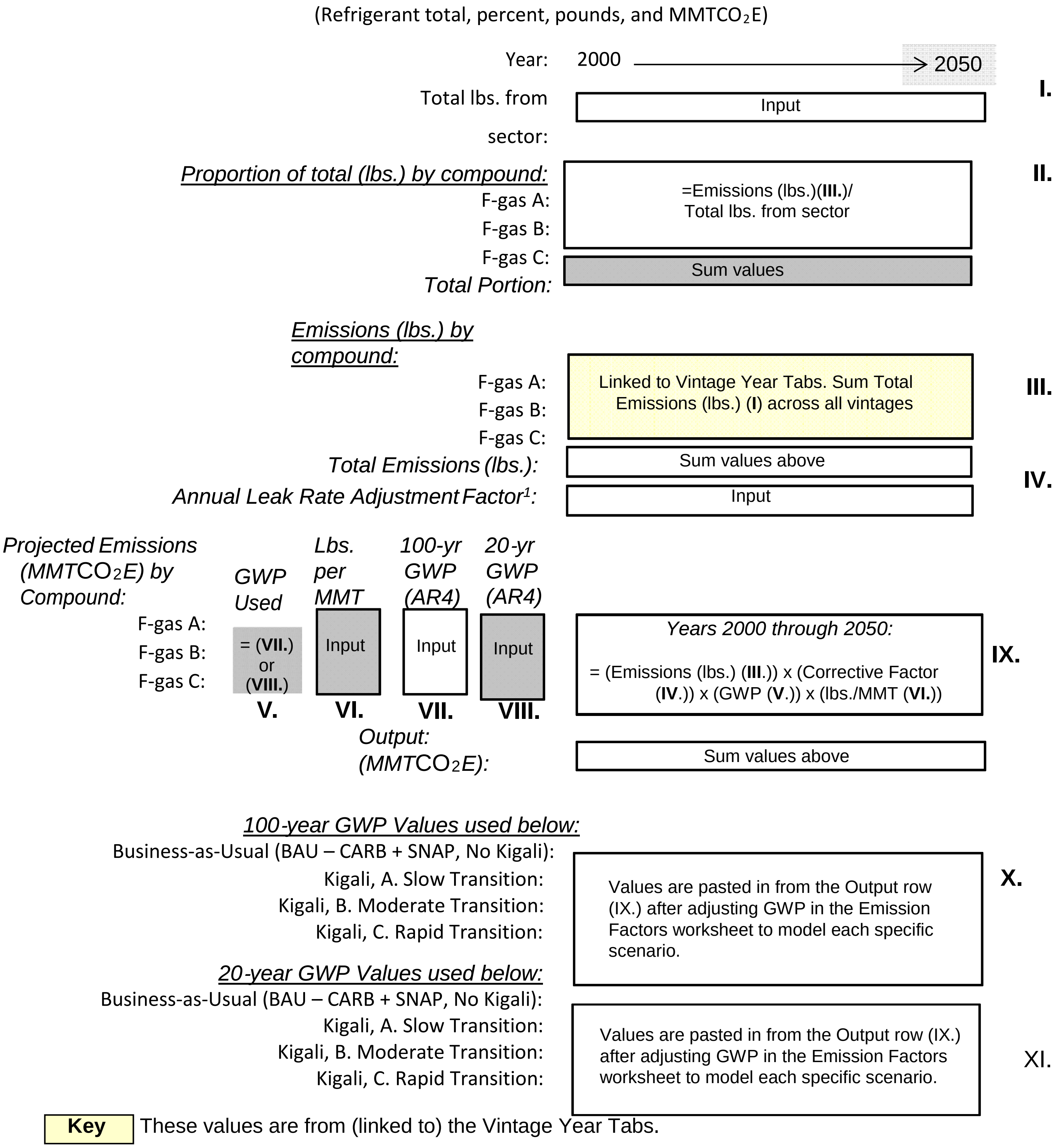


**Figure A4. Sum Emissions Worksheet.**



(Refrigerant total, percent, pounds, and $MMTCO_2E$)

Year: 2000 → 2050

I. Total lbs. from sector: Input

II. *Proportion of total (lbs.) by compound:*
F-gas A:
F-gas B:
F-gas C:
=Emissions (lbs.)(**III.**)/ Total lbs. from sector
*Total Portion:* Sum values

III. *Emissions (lbs.) by compound:*
F-gas A:
F-gas B:
F-gas C:
Linked to Vintage Year Tabs. Sum Total Emissions (lbs.) (**I**) across all vintages
*Total Emissions (lbs.):* Sum values above

IV. *Annual Leak Rate Adjustment Factor[1]:* Input

*Projected Emissions ($MMTCO_2E$) by Compound:*
F-gas A:
F-gas B:
F-gas C:

V. *GWP Used*: = (**VII.**) or (**VIII.**)
VI. *Lbs. per MMT*: Input
VII. *100-yr GWP (AR4)*: Input
VIII. *20-yr GWP (AR4)*: Input

IX. *Years 2000 through 2050:*
= (Emissions (lbs.) (**III.**)) x (Corrective Factor (**IV.**)) x (GWP (**V.**)) x (lbs./MMT (**VI.**))

*Output: ($MMTCO_2E$):* Sum values above

X. *100-year GWP Values used below:*
Business-as-Usual (BAU – CARB + SNAP, No Kigali):
Kigali, A. Slow Transition:
Kigali, B. Moderate Transition:
Kigali, C. Rapid Transition:
Values are pasted in from the Output row (IX.) after adjusting GWP in the Emission Factors worksheet to model each specific scenario.

XI. *20-year GWP Values used below:*
Business-as-Usual (BAU – CARB + SNAP, No Kigali):
Kigali, A. Slow Transition:
Kigali, B. Moderate Transition:
Kigali, C. Rapid Transition:
Values are pasted in from the Output row (IX.) after adjusting GWP in the Emission Factors worksheet to model each specific scenario.

**Key** These values are from (linked to) the Vintage Year Tabs.

[1] *The "Annual Leak Rate Adjustment Factor" is a ratio of current annual leak rate to baseline annual leak rates (updated annually from Refrigerant Management Program reported data).*

To further show the methodology used to estimate BAU emissions, we can use an example sector, residential window AC units (also called room AC units).

The basic idea is that we estimate the annual and life-time F-gas emissions from a given year's production throughout the lifetime of the equipment. The U.S. EPA calls this approach the "Vintaging Model". The model name refers to its tracking the use and emissions of annual "vintages" of equipment that enter service in a particular production year, with the equipment gradually reaching end-of-life.

The emissions from all years will overlap and aggregate for any type of equipment that is in use longer than one year. An abridged example follows:

**Table A5. Example of Aggregated Emissions from Multiple Production Years.**

| **Production Year:** | **Units produced** | **Emissions Year** | | | |
|---|---|---|---|---|---|
| | | **2012** | **2013** | **2014** | **2015** |
| **2012** | n | x $MTCO_2E$ | x $MTCO_2E$ | x $MTCO_2E$ | x $MTCO_2E$ |
| **2013** | n * (1+% annual growth) | | x $MTCO_2E$ | x $MTCO_2E$ | x $MTCO_2E$ |
| **2014** | n * (1+% annual growth)^$^2$ | | | x $MTCO_2E$ | x $MTCO_2E$ |
| **2015** | n * (1+% annual growth)^$^3$ | | | | x $MTCO_2E$ |

1) First we determine the number of new units produced or imported into the emissions region (in this case, California) each year. For new window AC units, data is tracked by the U.S. Census Bureau American Housing Survey (U.S. Census, 2016a). Where annual production of new units is not tracked, we can use the total number of units in operation, and divide by the average annual lifetime to find the annual replacement turnover. We then account for annual growth to estimate new units in a given year.

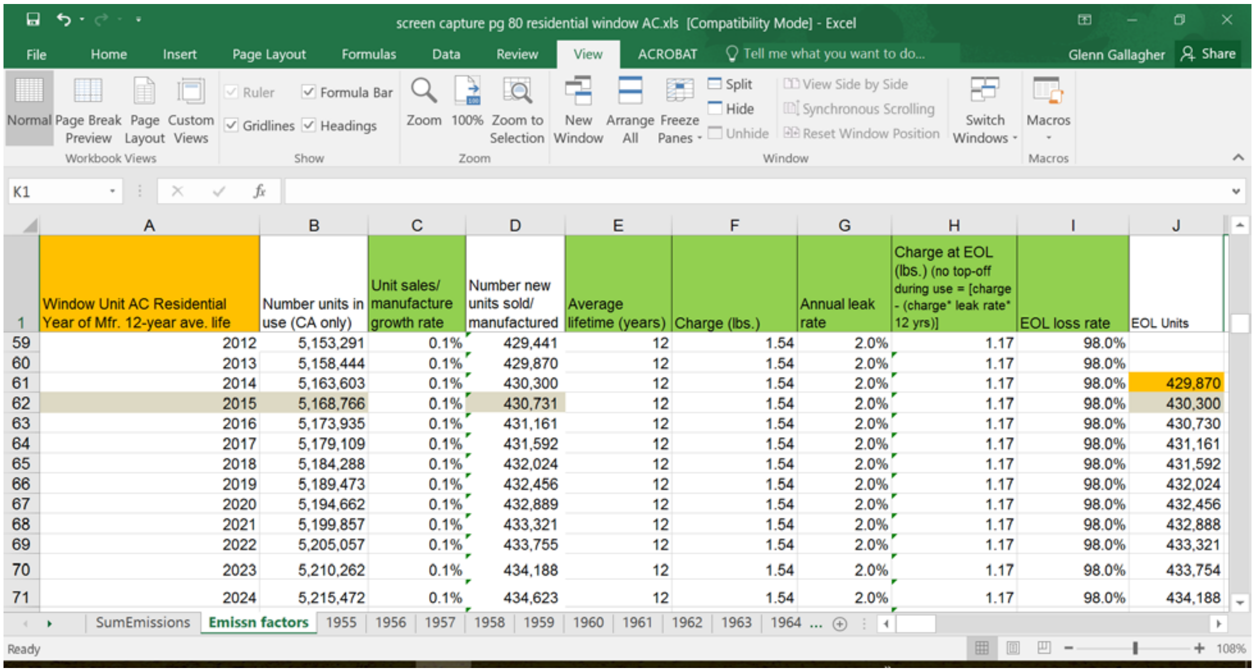
New units produced = (total number in use/annual lifetime in years) *(1 + annual growth rate).

2) In this example, we use calendar year 2015. From the U.S. Census data, we derive an estimate that there are 0.406 window (room) AC units per household, and by multiplying by 12,178,000 total households in California (U.S. Census, 2015), we arrive at 5,168,267 window units in California households in use in 2015. The number of new replacement units produced for California in 2015 would be approximately 430,700 (units/12 years average lifetime), + (new replacement units * annual growth rate in new equipment purchase/use).

3) Average charge size (amount of refrigerant in the unit), annual leak rate, end-of-life (EOL) loss rate, and typical refrigerants used in the equipment are then estimated. Research completed by Armines for CARB provided the data (Armines, 2009).

4) For each sector, an emissions spreadsheet is developed.

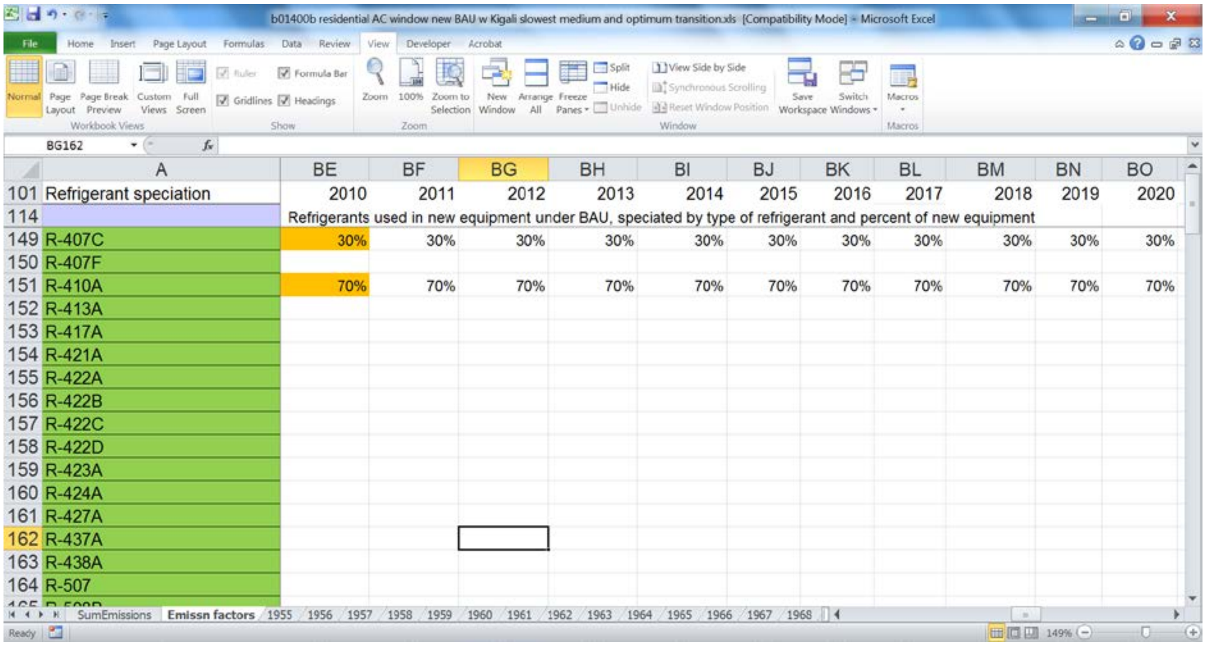
The following is a screen capture of the residential window AC units “emission factors” worksheet:



| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Window Unit AC Residential Year of Mfr. 12-year ave. life | Number units in use (CA only) | Unit sales/ manufacture growth rate | Number new units sold/ manufactured | Average lifetime (years) | Charge (lbs.) | Annual leak rate | Charge at EOL (lbs.) (no top-off during use = [charge - (charge* leak rate* 12 yrs)] | EOL loss rate | EOL Units |
| 59 | 2012 | 5,153,291 | 0.1% | 429,441 | 12 | 1.54 | 2.0% | 1.17 | 98.0% | |
| 60 | 2013 | 5,158,444 | 0.1% | 429,870 | 12 | 1.54 | 2.0% | 1.17 | 98.0% | |
| 61 | 2014 | 5,163,603 | 0.1% | 430,300 | 12 | 1.54 | 2.0% | 1.17 | 98.0% | 429,870 |
| 62 | 2015 | 5,168,766 | 0.1% | 430,731 | 12 | 1.54 | 2.0% | 1.17 | 98.0% | 430,300 |
| 63 | 2016 | 5,173,935 | 0.1% | 431,161 | 12 | 1.54 | 2.0% | 1.17 | 98.0% | 430,730 |
| 64 | 2017 | 5,179,109 | 0.1% | 431,592 | 12 | 1.54 | 2.0% | 1.17 | 98.0% | 431,161 |
| 65 | 2018 | 5,184,288 | 0.1% | 432,024 | 12 | 1.54 | 2.0% | 1.17 | 98.0% | 431,592 |
| 66 | 2019 | 5,189,473 | 0.1% | 432,456 | 12 | 1.54 | 2.0% | 1.17 | 98.0% | 432,024 |
| 67 | 2020 | 5,194,662 | 0.1% | 432,889 | 12 | 1.54 | 2.0% | 1.17 | 98.0% | 432,456 |
| 68 | 2021 | 5,199,857 | 0.1% | 433,321 | 12 | 1.54 | 2.0% | 1.17 | 98.0% | 432,888 |
| 69 | 2022 | 5,205,057 | 0.1% | 433,755 | 12 | 1.54 | 2.0% | 1.17 | 98.0% | 433,321 |
| 70 | 2023 | 5,210,262 | 0.1% | 434,188 | 12 | 1.54 | 2.0% | 1.17 | 98.0% | 433,754 |
| 71 | 2024 | 5,215,472 | 0.1% | 434,623 | 12 | 1.54 | 2.0% | 1.17 | 98.0% | 434,188 |

5.) Each new production year is then assigned the types of refrigerants used in the new equipment. In addition to the Armines research, we rely on estimates used in the U.S. EPA Vintaging Model (Godwin, et al., 2003; U.S. EPA, 2008; U.S. EPA 2016a). For window units made since 2010 when HCFC-22 was banned from new units, data indicate that 70% of new units use R-410A (a blend of 50% HFC-32 and 50% HFC-125), and 30% of new units use the HFC blend R-407C (52% HFC-134a, 25% HFC-125, and 23% HFC-32).

Refrigerant speciation for new equipment is shown on the following screen capture:



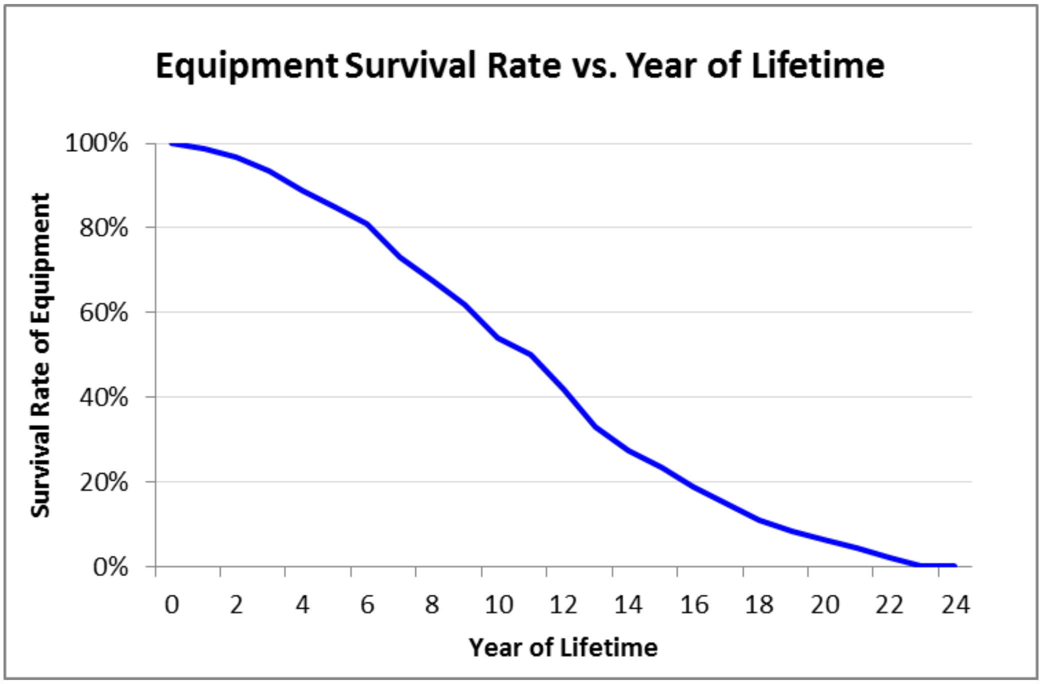
| | A | BE | BF | BG | BH | BI | BJ | BK | BL | BM | BN | BO |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 101 | Refrigerant speciation | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
| 114 | | Refrigerants used in new equipment under BAU, speciated by type of refrigerant and percent of new equipment | | | | | | | | | | |
| 149 | R-407C | 30% | 30% | 30% | 30% | 30% | 30% | 30% | 30% | 30% | 30% | 30% |
| 150 | R-407F | | | | | | | | | | | |
| 151 | R-410A | 70% | 70% | 70% | 70% | 70% | 70% | 70% | 70% | 70% | 70% | 70% |
| 152 | R-413A | | | | | | | | | | | |
| 153 | R-417A | | | | | | | | | | | |
| 154 | R-421A | | | | | | | | | | | |
| 155 | R-422A | | | | | | | | | | | |
| 156 | R-422B | | | | | | | | | | | |
| 157 | R-422C | | | | | | | | | | | |
| 158 | R-422D | | | | | | | | | | | |
| 159 | R-423A | | | | | | | | | | | |
| 160 | R-424A | | | | | | | | | | | |
| 161 | R-427A | | | | | | | | | | | |
| 162 | R-437A | | | | | | | | | | | |
| 163 | R-438A | | | | | | | | | | | |
| 164 | R-507 | | | | | | | | | | | |

6. Lifetime survival or retirement curves are applied for each sector. For window AC units, the average lifetime of 12 years means that approximately half will survive the first 12 years, with all equipment eventually retiring by twice the average lifetime, or 24 years.

Note that depending upon the type of equipment, a small fraction, generally two to three percent, will survive longer than twice the average lifetime. In CARB F-gas methodologies, we assume all equipment is retired by twice the average lifetime to simplify calculations. Equipment survival rates are from several sources (Calabrese, 2004; Lawless, 2003; Weibull, 1951; and Welch and Rogers, 2010).

The following figure shows the survival curve for equipment with a 12-year average lifetime:

**Figure A5. Equipment Survival Curve.**

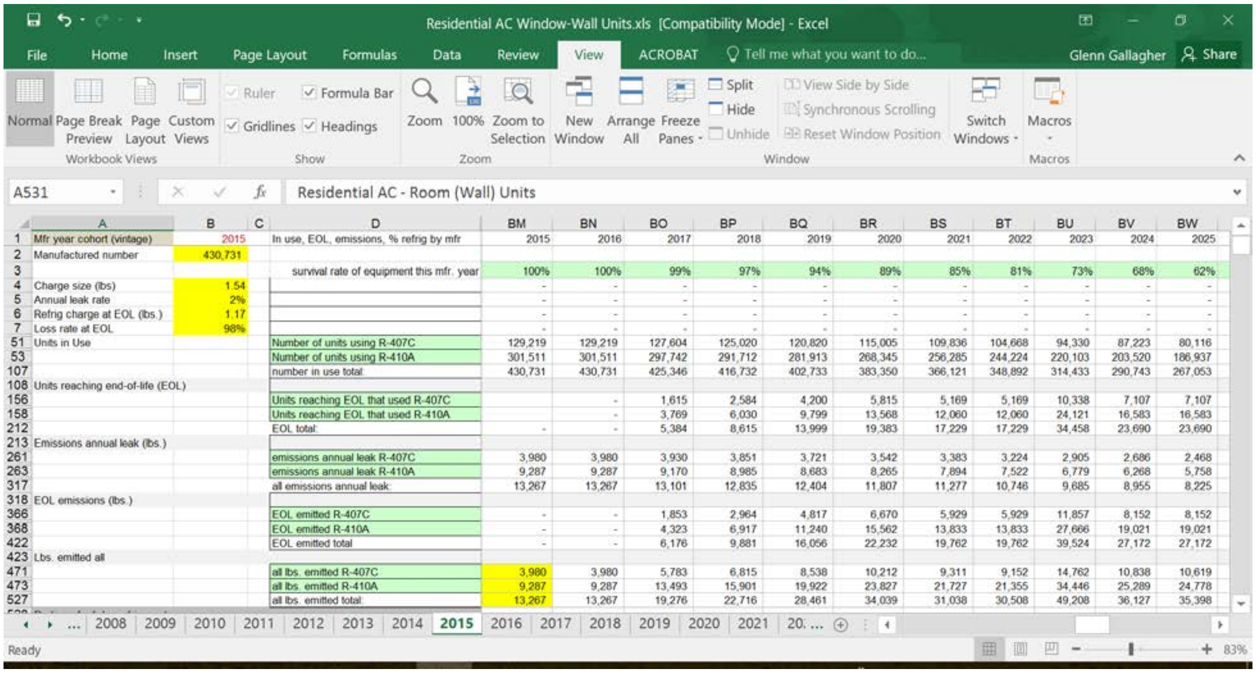


For consistency when comparing BAU emissions estimates to the lower GHG emissions that could be achieved by using low and lower-GWP refrigerants (in response to the global HFC phase-down), in this model we keep the following model parameters and emissions factors constant: charge size of refrigerant in kilograms or pounds, annual leak rates (percent of total charge lost each year), and end-of-life loss rates (percent of the total charge lost at equipment retirement end-of-life).

We also assume for BAU estimates, the initial refrigerant used at the time of production remains the refrigerant used throughout the equipment lifetime. In practice, the F-gas emissions model is updated annually to reflect average charge sizes in new equipment, average annual leak rates, average end-of-life loss rates, and types of refrigerants used in new equipment. The impact of retrofitting existing equipment with refrigerants that have significantly different (generally lower) GWP values, and the retrofit rates, will be added to future revisions to the model. Currently, emissions changes as a result of retrofits are applied in an added step after emissions have been estimated by initial modeling.

7. The emissions factors are applied to each year's production, where the "vintage" of new equipment and its emissions are tracked over the lifetime and survival curve of all units.

Here is a screen capture of just the 2015 "vintage" of units showing number of units in operation, units reaching end-of-life, and emissions in pounds by specific refrigerant.



Residential AC Window-Wall Units.xls [Compatibility Mode] - Excel

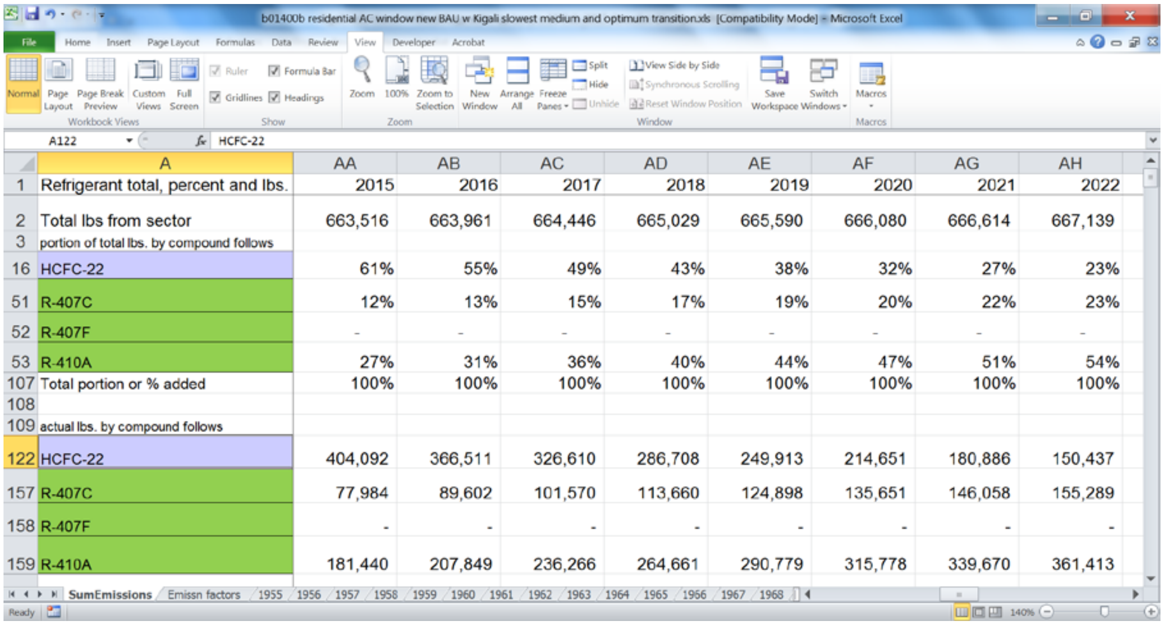
A531 Residential AC - Room (Wall) Units

| | A | B | C | D | BM | BN | BO | BP | BQ | BR | BS | BT | BU | BV | BW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Mfr year cohort (vintage) | 2015 | | In use, EOL, emissions, % refrig by mfr | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
| 2 | Manufactured number | 430,731 | | | | | | | | | | | | | |
| 3 | | | | survival rate of equipment this mfr. year | 100% | 100% | 99% | 97% | 94% | 89% | 85% | 81% | 73% | 68% | 62% |
| 4 | Charge size (lbs) | 1.54 | | | - | - | - | - | - | - | - | - | - | - | - |
| 5 | Annual leak rate | 2% | | | - | - | - | - | - | - | - | - | - | - | - |
| 6 | Refrig charge at EOL (lbs.) | 1.17 | | | - | - | - | - | - | - | - | - | - | - | - |
| 7 | Loss rate at EOL | 98% | | | - | - | - | - | - | - | - | - | - | - | - |
| 51 | Units in Use | | | Number of units using R-407C | 129,219 | 129,219 | 127,604 | 125,020 | 120,820 | 115,005 | 109,836 | 104,668 | 94,330 | 87,223 | 80,116 |
| 53 | | | | Number of units using R-410A | 301,511 | 301,511 | 297,742 | 291,712 | 281,913 | 268,345 | 256,285 | 244,224 | 220,103 | 203,520 | 186,937 |
| 107 | | | | number in use total: | 430,731 | 430,731 | 425,346 | 416,732 | 402,733 | 383,350 | 366,121 | 348,892 | 314,433 | 290,743 | 267,053 |
| 108 | Units reaching end-of-life (EOL) | | | | | | | | | | | | | | |
| 156 | | | | Units reaching EOL that used R-407C | | - | 1,615 | 2,584 | 4,200 | 5,815 | 5,169 | 5,169 | 10,338 | 7,107 | 7,107 |
| 158 | | | | Units reaching EOL that used R-410A | | - | 3,769 | 6,030 | 9,799 | 13,568 | 12,060 | 12,060 | 24,121 | 16,583 | 16,583 |
| 212 | | | | EOL total: | - | - | 5,384 | 8,615 | 13,999 | 19,383 | 17,229 | 17,229 | 34,458 | 23,690 | 23,690 |
| 213 | Emissions annual leak (lbs.) | | | | | | | | | | | | | | |
| 261 | | | | emissions annual leak R-407C | 3,980 | 3,980 | 3,930 | 3,851 | 3,721 | 3,542 | 3,383 | 3,224 | 2,905 | 2,686 | 2,468 |
| 263 | | | | emissions annual leak R-410A | 9,287 | 9,287 | 9,170 | 8,985 | 8,683 | 8,265 | 7,894 | 7,522 | 6,779 | 6,268 | 5,758 |
| 317 | | | | all emissions annual leak: | 13,267 | 13,267 | 13,101 | 12,835 | 12,404 | 11,807 | 11,277 | 10,746 | 9,685 | 8,955 | 8,225 |
| 318 | EOL emissions (lbs.) | | | | | | | | | | | | | | |
| 366 | | | | EOL emitted R-407C | - | - | 1,853 | 2,964 | 4,817 | 6,670 | 5,929 | 5,929 | 11,857 | 8,152 | 8,152 |
| 368 | | | | EOL emitted R-410A | - | - | 4,323 | 6,917 | 11,240 | 15,562 | 13,833 | 13,833 | 27,666 | 19,021 | 19,021 |
| 422 | | | | EOL emitted total | - | - | 6,176 | 9,881 | 16,056 | 22,232 | 19,762 | 19,762 | 39,524 | 27,172 | 27,172 |
| 423 | Lbs. emitted all | | | | | | | | | | | | | | |
| 471 | | | | all lbs. emitted R-407C | 3,980 | 3,980 | 5,783 | 6,815 | 8,538 | 10,212 | 9,311 | 9,152 | 14,762 | 10,838 | 10,619 |
| 473 | | | | all lbs. emitted R-410A | 9,287 | 9,287 | 13,493 | 15,901 | 19,922 | 23,827 | 21,727 | 21,355 | 34,446 | 25,289 | 24,778 |
| 527 | | | | all lbs. emitted total: | 13,267 | 13,267 | 19,276 | 22,716 | 28,461 | 34,039 | 31,038 | 30,508 | 49,208 | 36,127 | 35,398 |

In 2015, the first year of emissions from the 2015 vintage, emissions were calculated to be 3,980 lbs. of R-407C, and 9,287 lbs. of R-410A.

8. Each year’s equipment (vintage) emissions by specific refrigerant type are aggregated into one summary emissions worksheet. For each year, multiple vintages contribute to emissions. For example, 2015 emissions from window AC units with a 12-year average lifetime (and maximum lifetime of 24 years) contain emissions from equipment produced from 1991 through 2015.

The summary worksheet:



b01400b residential AC window new BAU w Kigali slowest medium and optimum transition.xls [Compatibility Mode] - Microsoft Excel

A122 HCFC-22

| | A | AA | AB | AC | AD | AE | AF | AG | AH |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Refrigerant total, percent and lbs. | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
| 2 | Total lbs from sector | 663,516 | 663,961 | 664,446 | 665,029 | 665,590 | 666,080 | 666,614 | 667,139 |
| 3 | portion of total lbs. by compound follows | | | | | | | | |
| 16 | HCFC-22 | 61% | 55% | 49% | 43% | 38% | 32% | 27% | 23% |
| 51 | R-407C | 12% | 13% | 15% | 17% | 19% | 20% | 22% | 23% |
| 52 | R-407F | - | - | - | - | - | - | - | - |
| 53 | R-410A | 27% | 31% | 36% | 40% | 44% | 47% | 51% | 54% |
| 107 | Total portion or % added | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| 108 | | | | | | | | | |
| 109 | actual lbs. by compound follows | | | | | | | | |
| 122 | HCFC-22 | 404,092 | 366,511 | 326,610 | 286,708 | 249,913 | 214,651 | 180,886 | 150,437 |
| 157 | R-407C | 77,984 | 89,602 | 101,570 | 113,660 | 124,898 | 135,651 | 146,058 | 155,289 |
| 158 | R-407F | - | - | - | - | - | - | - | - |
| 159 | R-410A | 181,440 | 207,849 | 236,266 | 264,661 | 290,779 | 315,778 | 339,670 | 361,413 |

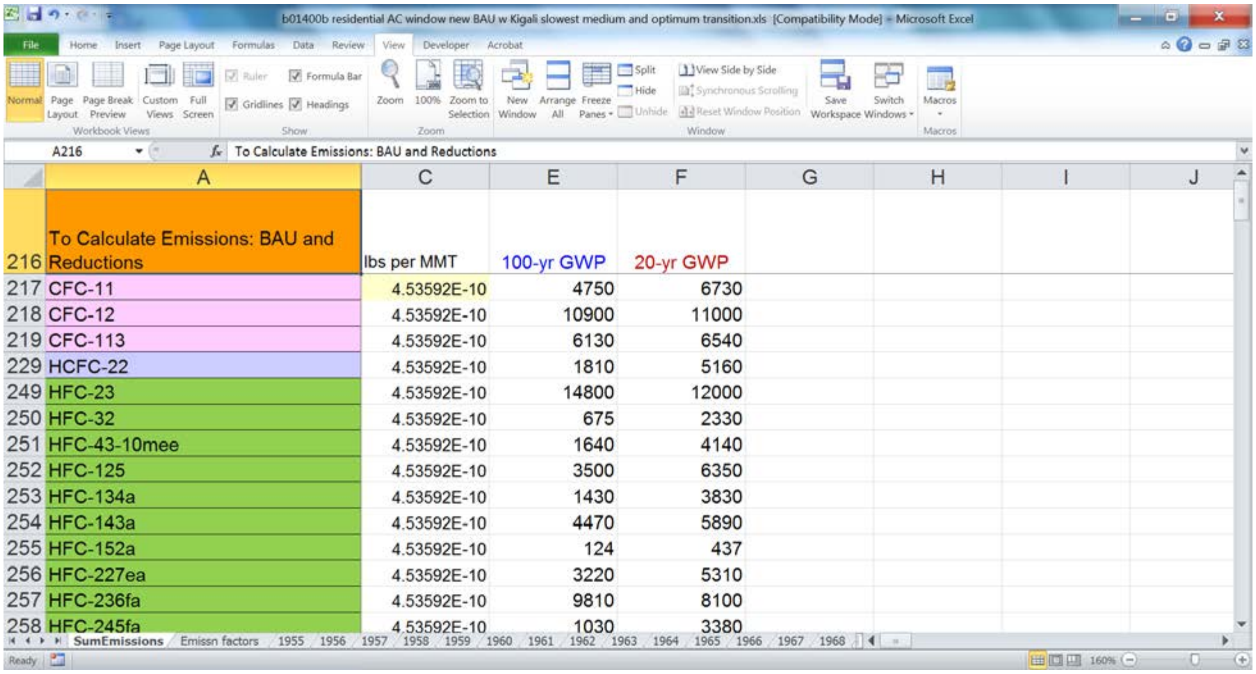
Note that although 2009 was the last year HCFC-22 was allowed in new refrigeration and air-conditioning equipment in the U.S., a full 61% of emissions in 2015 were still from older units containing HCFC-22. As the HCFC-22 units (no longer produced) age and reach end-of-life, their share of emissions declines to 23% by the year 2022. HCFC-22 emissions from window AC units made prior to 2010 are expected to continue through 2033.

9. Within the summary worksheet, we convert pounds of specific refrigerant to million metric tonne $CO_2$-equivalents ($MMTCO_2E$) using Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, 2007 (AR4) GWP values, for 100-year values (default), or 20-year values (as used in the Short-Lived Climate Pollutant [SLCP] Strategy).

To convert pounds of a refrigerant to $MMTCO_2E$:

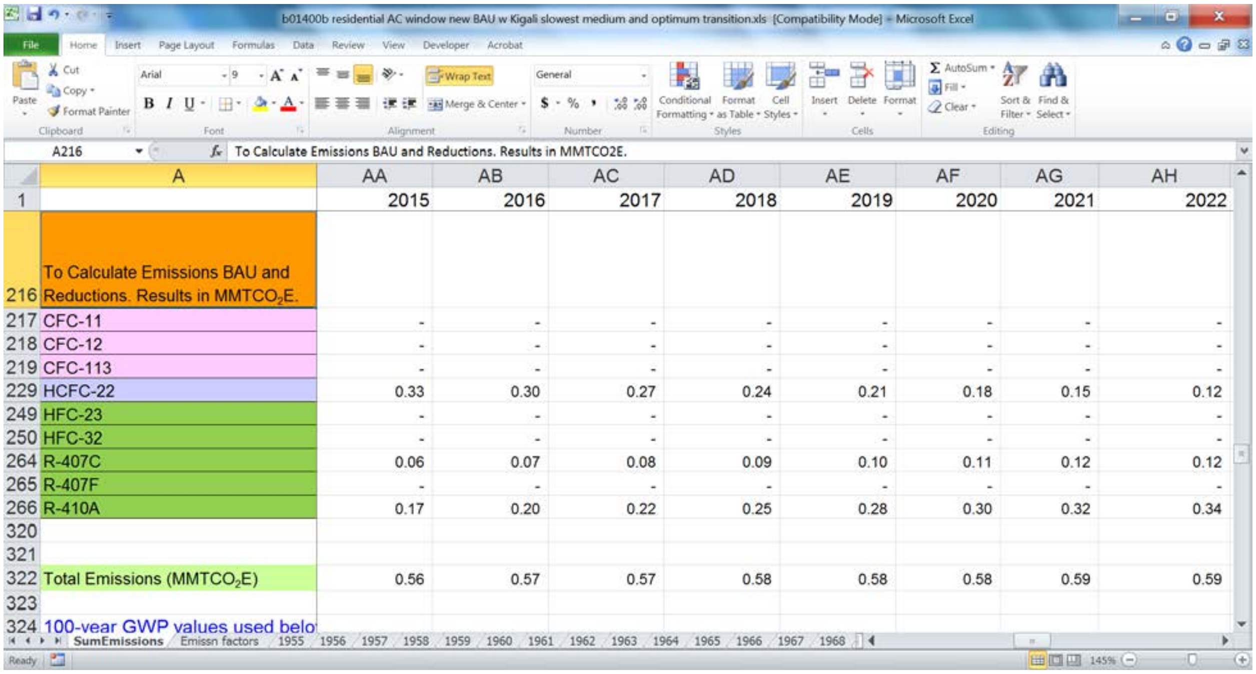
$MMTCO_2E$ = lbs. of refrigerant * GWP value of refrigerant* ($4.53592 * 10^{-10}$) MMT/pound

An abridged view of the GWP values listing in the summary worksheet:



| | A | C | E | F |
|---|---|---|---|---|
| 216 | To Calculate Emissions: BAU and Reductions | lbs per MMT | 100-yr GWP | 20-yr GWP |
| 217 | CFC-11 | 4.53592E-10 | 4750 | 6730 |
| 218 | CFC-12 | 4.53592E-10 | 10900 | 11000 |
| 219 | CFC-113 | 4.53592E-10 | 6130 | 6540 |
| 229 | HCFC-22 | 4.53592E-10 | 1810 | 5160 |
| 249 | HFC-23 | 4.53592E-10 | 14800 | 12000 |
| 250 | HFC-32 | 4.53592E-10 | 675 | 2330 |
| 251 | HFC-43-10mee | 4.53592E-10 | 1640 | 4140 |
| 252 | HFC-125 | 4.53592E-10 | 3500 | 6350 |
| 253 | HFC-134a | 4.53592E-10 | 1430 | 3830 |
| 254 | HFC-143a | 4.53592E-10 | 4470 | 5890 |
| 255 | HFC-152a | 4.53592E-10 | 124 | 437 |
| 256 | HFC-227ea | 4.53592E-10 | 3220 | 5310 |
| 257 | HFC-236fa | 4.53592E-10 | 9810 | 8100 |
| 258 | HFC-245fa | 4.53592E-10 | 1030 | 3380 |

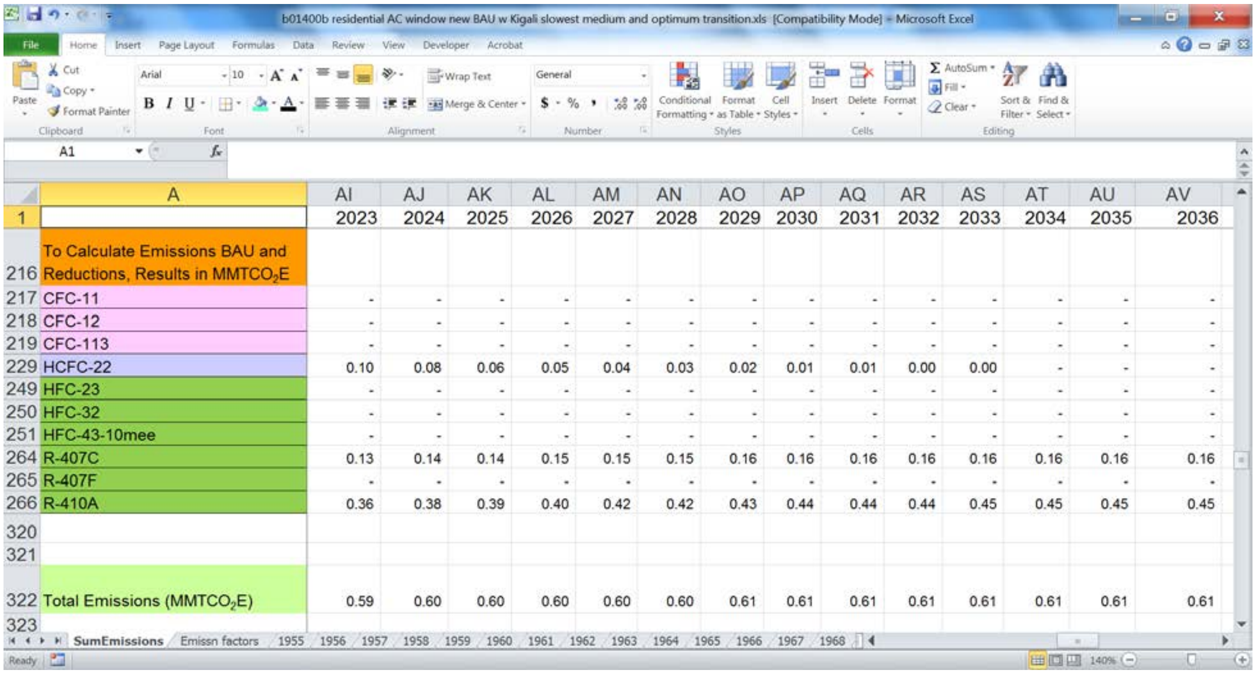
Emissions in MMTCO2E are calculated for each refrigerant:



A216 To Calculate Emissions BAU and Reductions. Results in MMTCO2E.

| | A | AA | AB | AC | AD | AE | AF | AG | AH |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
| 216 | To Calculate Emissions BAU and Reductions. Results in MMTCO$_2$E. | | | | | | | | |
| 217 | CFC-11 | - | - | - | - | - | - | - | - |
| 218 | CFC-12 | - | - | - | - | - | - | - | - |
| 219 | CFC-113 | - | - | - | - | - | - | - | - |
| 229 | HCFC-22 | 0.33 | 0.30 | 0.27 | 0.24 | 0.21 | 0.18 | 0.15 | 0.12 |
| 249 | HFC-23 | - | - | - | - | - | - | - | - |
| 250 | HFC-32 | - | - | - | - | - | - | - | - |
| 264 | R-407C | 0.06 | 0.07 | 0.08 | 0.09 | 0.10 | 0.11 | 0.12 | 0.12 |
| 265 | R-407F | - | - | - | - | - | - | - | - |
| 266 | R-410A | 0.17 | 0.20 | 0.22 | 0.25 | 0.28 | 0.30 | 0.32 | 0.34 |
| 320 | | | | | | | | | |
| 321 | | | | | | | | | |
| 322 | Total Emissions (MMTCO$_2$E) | 0.56 | 0.57 | 0.57 | 0.58 | 0.58 | 0.58 | 0.59 | 0.59 |
| 323 | | | | | | | | | |
| 324 | 100-year GWP values used belo | | | | | | | | |

We have calculated that total emissions from residential window AC units in 2015 are 0.56 MMTCO2E. However, note that because ozone-depleting substances (ODS) such as HCFC-22 are not included in the HFC emissions reductions goal of SB 1383, we include only the R-407C and R-410A HFC emissions of 0.23 MMTCO2E. For 2030 under BAU, the emissions of R-407C and R-410A would be 0.60 MMTCO2E. Emission years 2023-2036 are shown below for BAU.



| | A | AI | AJ | AK | AL | AM | AN | AO | AP | AQ | AR | AS | AT | AU | AV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 |
| 216 | To Calculate Emissions BAU and Reductions, Results in MMTCO$_2$E | | | | | | | | | | | | | | |
| 217 | CFC-11 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 218 | CFC-12 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 219 | CFC-113 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 229 | HCFC-22 | 0.10 | 0.08 | 0.06 | 0.05 | 0.04 | 0.03 | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 | - | - | - |
| 249 | HFC-23 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 250 | HFC-32 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 251 | HFC-43-10mee | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 264 | R-407C | 0.13 | 0.14 | 0.14 | 0.15 | 0.15 | 0.15 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |
| 265 | R-407F | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 266 | R-410A | 0.36 | 0.38 | 0.39 | 0.40 | 0.42 | 0.42 | 0.43 | 0.44 | 0.44 | 0.44 | 0.45 | 0.45 | 0.45 | 0.45 |
| 320 | | | | | | | | | | | | | | | |
| 321 | | | | | | | | | | | | | | | |
| 322 | Total Emissions (MMTCO$_2$E) | 0.59 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 |
| 323 | | | | | | | | | | | | | | | |

**Table A6. Additional reference table for BAU, percent HFC emissions by sector as of 2016, and average lifetime of HFC emissions sectors.**

| **HFC Emissions Sector** | **Percent of HFC Emissions by $CO_2E$** | **Average lifetime (years)** |
|---|---|---|
| Central Refrigeration, Large (2,000 + lbs.) | 2.6% | 15 |
| Central Refrigeration, Medium (200-2,000 lbs.) | 14.4% | 15 |
| Cold Storage, Large (2,000 + lbs.) | 0.8% | 20 |
| Cold Storage, Medium (200-2,000 lbs.) | 0.2% | 20 |
| Industrial Process Cooling (2,000 + lbs.) | 0.1% | 20 |
| Refrigerated Condensing Units, Small (50-200 lbs.) | 5.8% | 20 |
| Refrigerated Condensing Units, < 50 lbs. | 6.8% | 20 |
| Stand-alone (self-contained) Refrigeration | 0.5% | 20 |
| Refrigerated Vending Machines | 0.1% | 15 |
| AC Centrifugal Chiller, Large (≥2,000 lbs.) | 1.4% | 20 |
| AC Centrifugal Chiller, Medium (200-2,000 lbs.) | 0.1% | 20 |
| AC Packaged Chiller, Medium (200-2,000 lbs.) | 0.5% | 20 |
| AC Unitary Small (50-200 lbs.) | 2.7% | 15 |
| AC Unitary Sub-Small (< 50 lbs.) | 12.5% | 15 |
| AC Window Units, Commercial | 0.2% | 12 |
| Residential AC, Central | 13.2% | 15 |
| Residential AC, Window Units | 1.0% | 12 |
| Residential Refrigerator-Freezers | 1.0% | 14 |
| Motor Vehicle AC (MVAC), Light-Duty | 19.0% | 15 |
| MVAC Heavy-Duty: Bus, non-Bus On-Road, and Off-Road | 5.4% | 15 (bus); 10 (non-bus) |
| Transport Refrigerated Units | 2.0% | 12 |
| Refrigerated Shipping Containers | 0.8% | 5 |
| Insulating Foam | 2.8% | 15-30 |
| Fire Suppressants | 0.2% | 15 |
| Consumer Product Aerosol Propellants | 3.6% | <1 |
| Metered (Medical) Dose Inhaler (MDI) Propellants | 0.8% | <1 |
| Semiconductor Manufacturing | 0.4% | <1 |
| Solvents (non-semiconductor uses) | 1.0% | <1 |
| **Total** | **100.0%** | |

## Appendix B. Timeline of Class I ODS phase-out, Historical and Projected Refrigerant Trends in the U.S.; and CFC "Reductions Curve" applied to the HFC Phase-down Schedule

### Historical F-Gas Emissions Reductions, CFCs and other Class I ODS compounds

Empirical, reported data on Class I ODS emissions is readily available for the United States from 1990 through the present. (Class I ODS includes compounds with very high ozone-depleting potentials: CFCs, Halons, carbon tetrachloride, methyl chloroform, hydrobromofluorocarbons, and methyl bromide.) Actual emissions reductions as a result of an ODS phase-down, followed by a complete phase-out, can and should be used to inform analysis of likely emissions reductions that would occur under the HFC global phase-down schedule. A timeline of the Class I ODS phase-down-phase-out follows:

1974: Dr. F. Sherwood Rowland and Dr. Mario Molina hypothesize that CFCs damage the stratospheric ozone layer (later awarded the Nobel Prize in 1995 along with Paul J. Crutzen).

1975-1977: Many manufacturers voluntarily stop using CFC propellants in consumer product aerosols (Maxwell and Briscoe, 1997).

1978: The U.S. EPA ban CFCs as aerosol propellants in consumer product aerosols (exemptions made for medical dose inhalers and for aerosols used in limited technical uses) (U.S. EPA, 1990).

1985: Joe Farman, Brian Gardiner, and Jon Shanklin conduct ozone measurements and discover that a hole in the ozone layer above Antarctica existed, confirming the link between CFCs, HCFCs and ozone depletion.

1987: The Montreal Protocol on Substances that Deplete the Ozone Layer ("Montreal Protocol") international treaty designed to protect the ozone layer by phasing out the production of ozone depleting substances was ratified on 26 August 1987, eventually signed by all the members of the United Nations, and entered into force on 26 August 1989.

1990: Excise tax on CFCs begins in the United States (IRS, 2007).

1994: Ban on all new Halon consumption/production. Production/consumption of CFCs cut 75 percent compared to baseline year 1986, carbon tetrachloride and methyl chloroform cut 50 percent compared to baseline year 1989 (USC, 2013, and Federal Register, 1993). Most refrigeration and AC manufacturers phase out CFC refrigerants from new production chillers, refrigerators, motor vehicle air conditioners, and other products two or more years before the 1996 CFC consumption phase-out (U.S. EPA, 2014a).

1995: Consumption/production of CFCs remains at 75 percent below baseline. Carbon tetrachloride cut 85 percent, methyl chloroform cut 70 percent.

1996: Ban on all new production and consumption of CFCs, carbon tetrachloride, methyl chloroform, and hydrobromofluorocarbons.

2005: Methyl bromide not completely phased out until 2005, although with a 100-year GWP of five, its GHG emissions are negligible compared to CFCs (US EPA, 2017d).

Of all the Class I ODS, CFCs are better representatives of future HFC emissions reductions than the grouping of all Class I ODS combined, because CFC and non-CFC solvents combined represented 17 percent of all Class I ODS emissions, while solvents represent 1.4 percent of HFC emissions. (The major non-CFC solvents used were carbon tetrachloride and methyl chloroform.) Solvents are treated as fully emissive the first year of their production. Therefore, Class I ODS solvent reductions would be extremely rapid compared to the non-solvents, and the results would be skewed towards over-representation of early reductions.

The Class I ODS fire suppressants, Halons, represent the other extreme in emissions, where emissions are quite low but may continue for decades after production. Halons are considered so valuable, that they have been carefully stored by the U.S. military for decades. Halon emissions are rare. Halons were less than one percent of Class I ODS emissions from 1990 through 1995, and they are not included in the CFC emissions reductions analysis.

**Table B1. Historical and Projected Refrigerant Trends in the United States.**

| Years | Predominant Refrigerant used in new equipment | Average GWP[1] | Notes[2] |
|---|---|---|---|
| 1930-1994 | CFCs | 8755 | CFC emissions continue through 2030 |
| 1995-2009 | HCFCs | 1720 | HCFC emissions continue through 2045 |
| 2010 – 2019 | HFCs | 1967 | High-GWP HFC emissions continue through 2055 |
| 2020 - 2050 | HFOs, $CO_2$, ammonia, hydrocarbons, HFO-HFC blends | <1967 and decreasing through 2036, ≈ 230 by 2040-2045 | Unknown in short-term, but GWP should stabilize at (15% * HCFC average + 85% HFC average)* (100% -85% production cut) |

Table notes.

1) If we include HFC-152a with a GWP of 124, the average GWP is reduced to 1495 for all HFC uses, however, HFC-152a is almost exclusively used as an aerosol propellant, with minor use as an insulating foam expansion agent, and negligible use as a refrigerant. While the transition from CFCs to HCFCs resulted in a significant 80 percent reduction in the average GWP of refrigerants, the next transition from HCFCs to HFCs actually increased the average GWP by 14 percent.

2) As estimated by the CARB F-gas Inventory Estimates and described in Gallagher, et al., 2014.

Over the long-term, we expect the average GWP of refrigerants to decrease as high-GWP HFCs are gradually phased out of production. However, both modeling and historical data show that the emissions of the high-GWP refrigerants continue for decades after they are banned in new equipment, without additional measures such as prohibitions of high-GWP refrigerants in new equipment, or required retrofits such as a servicing ban on adding additional high-GWP refrigerant to existing equipment.

### CFC “reductions curve” applied to the HFC phase-down schedule

Table B3 on the following pages is from the calculation spreadsheet where the CFC reductions curve (actual historical reductions rates) is applied to each separate HFC phase-down step. One way to think of this approach is that a “total phase-down” rate from CFC data is applied to a given phase-down. For example, the 40% reduction step in 2024 is tracked over the next 22 years, the average time it takes for HFC-using equipment to complete their lifecycle. Each step is similarly tracked, with separate phase-down steps overlapping in time. Because the CFC emissions trends are the result of all emissions factors (leak rates, equipment stock, retrofit rates, etc.,) it is an algebraic model of emissions reductions very different and much simpler than the Vintaging-type model used to estimate emissions from the scenarios of business-as-usual (baseline), “best case”, and “worst case”.

To avoid double-counting the reduction steps, we use the additional reductions gained from each phase-down step to calculate reductions from a given step, as shown below.

**Table B2. Additional reductions from each phase-down step.**

| Year | Production/ Consumption Cap | Reductions in Production/ Consumption | Additional Reductions from previous phase-down step |
|---|---|---|---|
| 2019 | 90% | 10% | 10% |
| 2024 | 60% | 40% | 30% |
| 2029 | 30% | 70% | 30% |
| 2034 | 20% | 80% | 10% |
| 2036 | 15% | 85% | 5% |

## Table B3. CFC Reductions Curve Applied to HFC Phase-down Steps – Results. (Page 1 of 3)

| Year | 2019 phase-down step: 10% (no effect until next phase-down step in 2024 begins) | Relative reductions of the 2019 10% goal (using the CFC reductions curve) | Actual % reductions from baseline due to 2019 10% phase-down; annual (phase-down % * reductions curve %) | | 2024 phase-down step: 40% (affects new units 2023-2028 and throughout equip. life); add'l step reduction 40% - 10% = 30% | Relative reductions of the 2024 40% goal (using the CFC reductions curve) | Actual % reductions from baseline due to 2024 40% phase-down; annual (additional phase-down % * reductions curve %) |
|---|---|---|---|---|---|---|---|
| 2018 | | | | | | | |
| 2019 | 0% | 15.0% | 0.0% | | | | |
| 2020 | 0% | 11.0% | 0.0% | | | | |
| 2021 | 0% | 7.0% | 0.0% | | | | |
| 2022 | 0% | 6.0% | 0.0% | | | | |
| 2023 | 0% | 6.0% | 0.0% | | | | |
| 2024 | 10% | 5.0% | 0.5% | | 30% | 15.0% | 4.5% |
| 2025 | 10% | 5.0% | 0.5% | | 30% | 11.0% | 3.3% |
| 2026 | 10% | 5.0% | 0.5% | | 30% | 7.0% | 2.1% |
| 2027 | 10% | 4.0% | 0.4% | | 30% | 6.0% | 1.8% |
| 2028 | 10% | 4.0% | 0.4% | | 30% | 6.0% | 1.8% |
| 2029 | 10% | 4.0% | 0.4% | | 30% | 5.0% | 1.5% |
| 2030 | 10% | 3.0% | 0.3% | | 30% | 5.0% | 1.5% |
| 2031 | 10% | 3.0% | 0.3% | | 30% | 5.0% | 1.5% |
| 2032 | 10% | 3.0% | 0.3% | | 30% | 4.0% | 1.2% |
| 2033 | 10% | 3.0% | 0.3% | | 30% | 4.0% | 1.2% |
| 2034 | 10% | 2.0% | 0.2% | | 30% | 4.0% | 1.2% |
| 2035 | 10% | 2.0% | 0.2% | | 30% | 3.0% | 0.9% |
| 2036 | 10% | 2.0% | 0.2% | | 30% | 3.0% | 0.9% |
| 2037 | 10% | 2.0% | 0.2% | | 30% | 3.0% | 0.9% |
| 2038 | 10% | 1.0% | 0.1% | | 30% | 3.0% | 0.9% |
| 2039 | 10% | 1.0% | 0.1% | | 30% | 2.0% | 0.6% |
| 2040 | 10% | 1.0% | 0.1% | | 30% | 2.0% | 0.6% |
| 2041 | 10% | 0.0% | 0.0% | | 30% | 2.0% | 0.6% |
| 2042 | 10% | 0.0% | 0.0% | | 30% | 2.0% | 0.6% |
| 2043 | 10% | 0.0% | 0.0% | | 30% | 1.0% | 0.3% |
| 2044 | 10% | - | - | | 30% | 1.0% | 0.3% |
| 2045 | 10% | - | - | | 30% | 1.0% | 0.3% |
| 2046 | 10% | - | - | | 30% | 0.0% | 0.0% |
| 2047 | 10% | - | - | | 30% | 0.0% | 0.0% |
| 2048 | 10% | - | - | | 30% | 0.0% | 0.0% |
| 2049 | 10% | | - | | 30% | - | - |
| 2050 | 10% | | - | | 30% | - | - |

Phase-down steps for 2029 (70%) and 2034 (80%) are shown on the following page.

## Table B3. Continued. (Page 2 of 3)

| Year | 2029 phase-down step: 70% (affects new units 2029-2033 and throughout equip. life) add'l step reduction 70% - 40% = 30% | Relative reductions of the 2029 70% goal (using the CFC reductions curve) | Actual % reductions from baseline due to 2029 70% phase-down; annual (additional phase-down % * reductions curve %) |  | 2034 phase-down step: 80% (affects new units 2034-2035 and throughout equip. life) add'l step reduction 80% - 70% = 10% | Relative reductions of the 2034 80% goal (using the CFC reductions curve) | Actual % reductions from baseline due to 2034 80% phase-down; annual (additional phase-down % * reductions curve %) |
|---|---|---|---|---|---|---|---|
| 2018 |  |  |  |  |  |  |  |
| 2019 |  |  |  |  |  |  |  |
| 2020 |  |  |  |  |  |  |  |
| 2021 |  |  |  |  |  |  |  |
| 2022 |  |  |  |  |  |  |  |
| 2023 |  |  |  |  |  |  |  |
| 2024 |  |  |  |  |  |  |  |
| 2025 |  |  |  |  |  |  |  |
| 2026 |  |  |  |  |  |  |  |
| 2027 |  |  |  |  |  |  |  |
| 2028 |  |  |  |  |  |  |  |
| 2029 | 30% | 15.0% | 4.5% |  |  |  |  |
| 2030 | 30% | 11.0% | 3.3% |  |  |  |  |
| 2031 | 30% | 7.0% | 2.1% |  |  |  |  |
| 2032 | 30% | 6.0% | 1.8% |  |  |  |  |
| 2033 | 30% | 6.0% | 1.8% |  |  |  |  |
| 2034 | 30% | 5.0% | 1.5% |  | 10% | 15.0% | 1.5% |
| 2035 | 30% | 5.0% | 1.5% |  | 10% | 11.0% | 1.1% |
| 2036 | 30% | 5.0% | 1.5% |  | 10% | 7.0% | 0.7% |
| 2037 | 30% | 4.0% | 1.2% |  | 10% | 6.0% | 0.6% |
| 2038 | 30% | 4.0% | 1.2% |  | 10% | 6.0% | 0.6% |
| 2039 | 30% | 4.0% | 1.2% |  | 10% | 5.0% | 0.5% |
| 2040 | 30% | 3.0% | 0.9% |  | 10% | 5.0% | 0.5% |
| 2041 | 30% | 3.0% | 0.9% |  | 10% | 5.0% | 0.5% |
| 2042 | 30% | 3.0% | 0.9% |  | 10% | 4.0% | 0.4% |
| 2043 | 30% | 3.0% | 0.9% |  | 10% | 4.0% | 0.4% |
| 2044 | 30% | 2.0% | 0.6% |  | 10% | 4.0% | 0.4% |
| 2045 | 30% | 2.0% | 0.6% |  | 10% | 3.0% | 0.3% |
| 2046 | 30% | 2.0% | 0.6% |  | 10% | 3.0% | 0.3% |
| 2047 | 30% | 2.0% | 0.6% |  | 10% | 3.0% | 0.3% |
| 2048 | 30% | 1.0% | 0.3% |  | 10% | 3.0% | 0.3% |
| 2049 | 30% | 1.0% | 0.3% |  | 10% | 2.0% | 0.2% |
| 2050 | 30% | 1.0% | 0.3% |  | 10% | 2.0% | 0.2% |

The final phase-down step in 2036 (85%) and the aggregated reductions (absolute percent reductions from baseline emissions) are shown on the following page.

## Table B3. Continued. (Page 3 of 3)

| Year | 2036 phase-down step: 85% (affects new units 2036 onward) add'l step reduction 85% - 80% = 5% | Relative reductions of the 2036 85% goal (using the CFC reductions curve) | Actual % reductions from baseline due to 2036 85% phase-down; annual | | Actual % reductions (annual) from baseline; all phase-down steps aggregated; total reduction in consumption is 85% | Cumulative reductions | Emissions compared to baseline 100% |
|---|---|---|---|---|---|---|---|
| 2018 | | | | | 0% | | |
| 2019 | | | | | 0.0% | 0.0% | 100.0% |
| 2020 | | | | | 0.0% | 0.0% | 100.0% |
| 2021 | | | | | 0.0% | 0.0% | 100.0% or more |
| 2022 | | | | | 0.0% | 0.0% | 100.0% or more |
| 2023 | | | | | 0.0% | 0.0% | 100.0% or more |
| 2024 | | | | | 5.0% | 5.0% | 95.0% |
| 2025 | | | | | 3.8% | 8.8% | 91.2% |
| 2026 | | | | | 2.6% | 11.4% | 88.6% |
| 2027 | | | | | 2.2% | 13.6% | 86.4% |
| 2028 | | | | | 2.2% | 15.8% | 84.2% |
| 2029 | | | | | 6.4% | 22.2% | 77.8% |
| 2030 | | | | | 5.1% | 27.3% | 72.7% |
| 2031 | | | | | 3.9% | 31.2% | 68.8% |
| 2032 | | | | | 3.3% | 34.5% | 65.5% |
| 2033 | | | | | 3.3% | 37.8% | 62.2% |
| 2034 | | | | | 4.4% | 42.2% | 57.8% |
| 2035 | | | | | 3.7% | 45.9% | 54.1% |
| 2036 | 5% | 15.0% | 0.8% | | 4.1% | 50.0% | 50.1% |
| 2037 | 5% | 11.0% | 0.6% | | 3.5% | 53.4% | 46.6% |
| 2038 | 5% | 7.0% | 0.4% | | 3.2% | 56.6% | 43.5% |
| 2039 | 5% | 6.0% | 0.3% | | 2.7% | 59.2% | 40.8% |
| 2040 | 5% | 6.0% | 0.3% | | 2.4% | 61.6% | 38.4% |
| 2041 | 5% | 5.0% | 0.3% | | 2.3% | 63.9% | 36.1% |
| 2042 | 5% | 5.0% | 0.3% | | 2.2% | 66.2% | 33.9% |
| 2043 | 5% | 5.0% | 0.3% | | 1.9% | 68.1% | 32.0% |
| 2044 | 5% | 4.0% | 0.2% | | 1.5% | 69.6% | 30.4% |
| 2045 | 5% | 4.0% | 0.2% | | 1.4% | 70.9% | 29.1% |
| 2046 | 5% | 4.0% | 0.2% | | 1.3% | 72.3% | 27.7% |
| 2047 | 5% | 3.0% | 0.2% | | 1.3% | 73.5% | 26.5% |
| 2048 | 5% | 3.0% | 0.2% | | 0.9% | 74.4% | 25.6% |
| 2049 | 5% | 3.0% | 0.2% | | 0.7% | 75.2% | 24.8% |
| 2050 | 5% | 3.0% | 0.2% | | 0.7% | 75.9% | 24.2% |

## Appendix C. HFC End-Use Sectors with no Likely Additional Reductions from the Kigali Amendment HFC Phase-down

Due to the CARB and U.S. EPA regulations already in place, new equipment and materials are expected to be lower-GWP by 2021 as part of the projected BAU emissions of HFCs in California. Therefore, the HFC phase-down will have little to no reductions effect on several end-use sectors, which in turn allows more high-GWP HFCs available for other sectors, with the net result that emissions reductions are reduced and delayed. Additional details are included in the following table.

**Table C1. HFC End-Use Sectors with no Likely Reductions from HFC Phase-down.**

| HFC Sectors with no Likely Reductions from Kigali HFC Phase-down | Notes |
|---|---|
| Metered (medical) dose inhalers | Metered dose inhalers (MDIs) were allowed to use CFCs until 2013; an additional 18 years after most CFC uses were banned in 1995, due to their importance in health, and the difficulty in reformulating the product to use alternate propellants. Currently, MDIs using F-gases use HFC-134a (GWP 1430) by itself or blended with HFC-227ea (GWP 3220). Given the immense cost of reformulating products again and the medical necessity of MDIs, it is not likely that MDIs will stop using HFCs as a result of the Kigali Phase-down. MDI annual emissions in CA are estimated at 0.16 $MMTCO_2E$, or 0.8% of all HFC emissions in CA. |
| Light-Duty Motor Vehicle Air-conditioning (MVAC) | The U.S. EPA Significant New Alternatives Policy (SNAP) Program has listed the default refrigerant, HFC-134a, as unacceptable in New Light-Duty MVAC Systems as of Model Year (MY) 2021. Substitutes include HFO-1234yf (GWP < 10) and $CO_2$ (GWP 1). |
| Residential refrigerator-freezer | The U.S. EPA SNAP Program has listed HFC-134a as unacceptable in new units beginning January 1, 2021. HFO-HFC blends have been approved for new equipment, including R-450A (GWP 601) and R-513A (GWP 630). However, the appliance industry has indicated they prefer to transition from HFC-134a directly to hydrocarbon refrigerants such as isobutane (R-600a, GWP 3) without using a transitional high-GWP refrigerant as an interim solution. |

| **HFC Sectors with no Likely Reductions from Kigali HFC Phase-down** | **Notes** |
|---|---|
| Insulating foam | The U.S. EPA SNAP Program has listed the baseline foam expansion agents of HFC-134a and HFC-245fa as unacceptable in new production beginning in 2022. |
| Stand-alone (self-contained) refrigerated display cases and refrigeration units | U.S. EPA SNAP Program revisions made July 20, 2015 changed the listing of most high-GWP HFCs (used in new stand-alone equipment) from acceptable to unacceptable by January 1, 2020. The SNAP Program is careful not to list specific GWP thresholds when relisting refrigerants, although it appears that no refrigerants with a GWP greater than 1500 will be allowed in new equipment. The standard refrigerant used today is R-404A with a GWP of 3922; therefore, estimated emissions reductions due to the SNAP Program changes will be greater than 60% from this sector. |
| Refrigerated vending machines | The baseline refrigerant of HFC-134a has been listed as unacceptable in new equipment beginning January 1, 2019 by the U.S. EPA SNAP Program. Many units are currently manufactured using hydrocarbon refrigerants or $CO_2$. |
| Chillers – Centrifugal and Positive Displacement | The U.S. EPA SNAP Program also listed high-GWP HFCs as unacceptable for new chillers beginning January 1, 2024. Based on current low-GWP chiller technology available, pure HFOs are the most likely refrigerants that will be used to meet the SNAP changes. |
| Fire suppressants | Negligible HFC emissions, not modeled for reductions. Fire suppressants using ozone-depleting Halons largely transitioned to non-F-gas substitutes. The following HFCs are still used in small amounts in some new units: HFC-125 (GWP 3500), HFC-227ea (GWP 3220), and HFC-236fa (GWP 9810). In 2016 in California, HFC emissions from fire suppressants were estimated at 0.04 $MMTCO_2E$, or 0.2% of all HFC emissions. |
| Semiconductor manufacturing | Relatively negligible HFC emissions of 0.1 $MMTCO_2E$, or 0.4% of all HFC emissions in CA in 2016, and not modeled further for potential reductions. F-gas emissions from semiconductor manufacturing are already highly regulated by CARB, with perfluorocarbon (PFC), sulfur hexafluoride ($SF_6$), and nitrogen trifluoride ($NF_3$) emissions comprising 86% of all F-gas emissions from this sector. PFCs, $SF_6$, and $NF_3$ are not covered by the Kigali HFC Phase-down Amendment. |

## Appendix D. Impact on Emissions from Servicing Demand and Retrofits

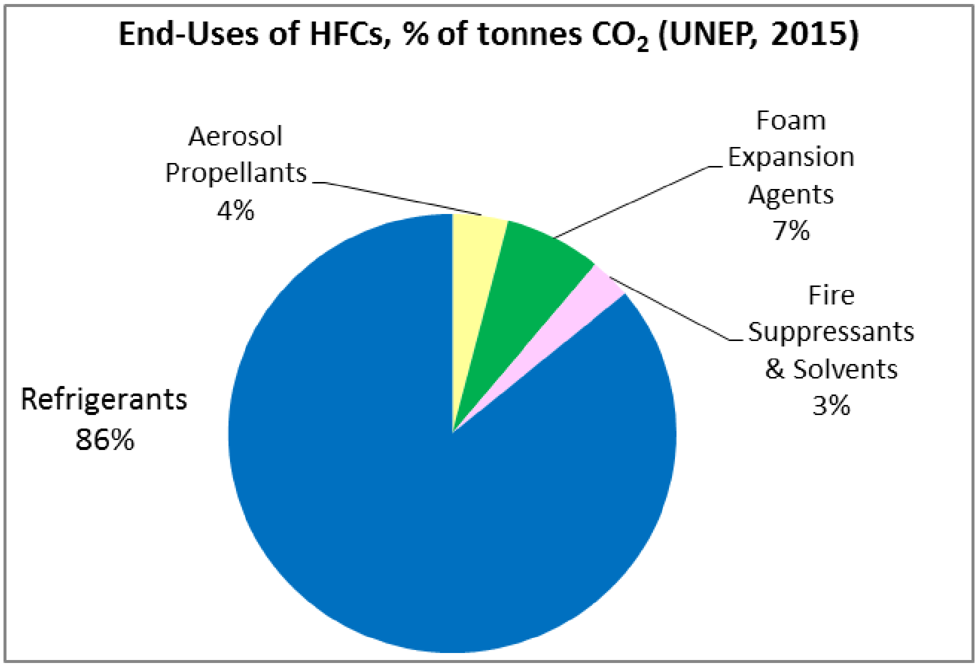
A description of how servicing demand can further reduce HFC emissions follows.

Servicing demand was not specifically modeled in the ODS reductions scenarios, although the impact by servicing demand is definitely included and reflected in the actual emissions data. The “worst case” scenario assumes a weak servicing demand by existing equipment on newly manufactured lower-GWP HFCs and substitutes; existing equipment would use HFCs that had been stockpiled, illegally imported, or recycled (although no additional recycling/recovery of refrigerants beyond BAU is assumed for the worst-case scenario). The “best case” scenario assumes a strong servicing demand of newly manufactured HFCs by existing equipment.

HFC supply reductions will not just affect new equipment, it will also constrain the supply of available HFCs to service existing equipment (replacing leaked refrigerant). Servicing demand will accelerate HFC reductions by two primary modes:

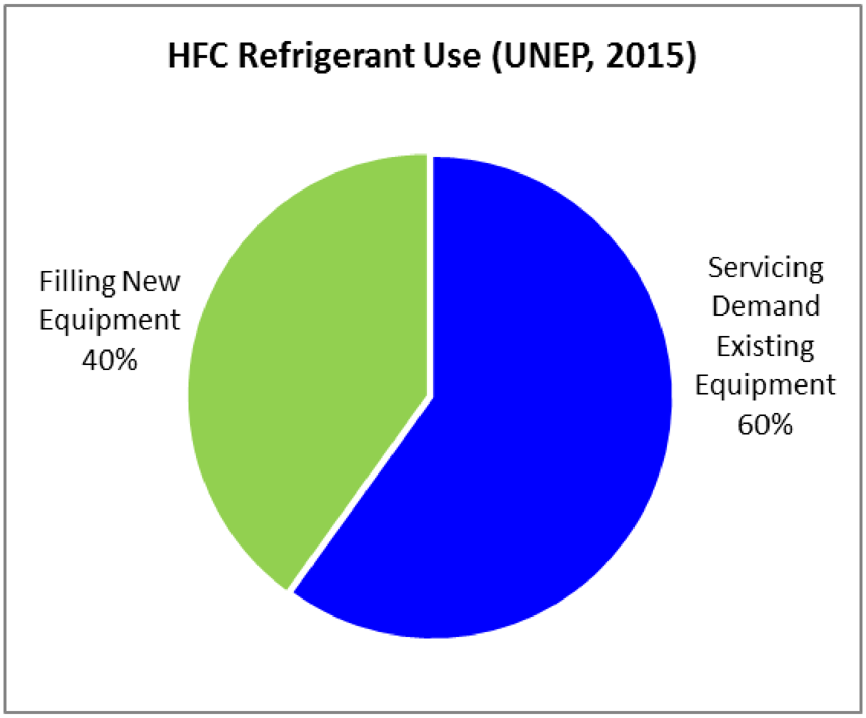
First mode of reduction: Existing equipment will continue to use available high-GWP HFCs, which in turn will compete for a diminishing supply of high-GWP HFCs for new equipment. The probable result is that new equipment will use significantly lower GWP HFCs (or replacements) than baseline. The United Nations Environment Programme (UNEP) estimates that 86% of all HFCs ($CO_2$-equivalents) produced globally are used as refrigerants as shown in the following figure (UNEP, 2015).

**Figure D1. Global End-Uses of HFCs as % tonnes of $CO_2$-equivalents**



UNEP also estimates that of the refrigerants manufactured each year, approximately 60 percent go to servicing demand of existing equipment to replace lost refrigerant, also known as “topping off leaks”.

**Figure D2. HFC Refrigerant Use, Filling New Equipment vs. Servicing Demand of Existing Equipment**



Using the UNEP data showing that 86 percent of HFCs are refrigerants, and that 60 percent of refrigerants manufactured are for the servicing demand of existing equipment (replacing refrigerant lost due to leaks), we can estimate that 86% * 60%, or 52% of all HFCs produced, about half, are currently used to service existing refrigeration and air-conditioning equipment.

In developed countries such as the United States that has a more mature and “saturated” refrigeration and air-conditioning market, the amount of HFCs (in $CO_2$-equivalents) used for servicing is estimated at 70% of all new HFC production, higher than the 60% used internationally, which takes into account the rapid growth of new equipment in the developing countries. In this context, the amount of HFCs produced to service existing equipment using refrigerants is 86% of HFCs are refrigerants * 70% servicing demand = 60% of all HFCs produced are for refrigeration and AC servicing demand of existing equipment.

Second mode of reduction: Retrofits. As the supply of high-GWP HFCs is reduced, they will become scarcer, and presumably more expensive. Existing equipment using high-GWP HFCs may replace their refrigerant with a lower-GWP substitute, a process known as a “retrofit”. Emissions reductions occur during the remaining lifetime of the equipment where the new lower-GWP refrigerant is emitted rather than the original high-GWP refrigerant initially used in the equipment. It is not possible to predict the rate of retrofits due to the global HFC phase-down.

Retrofits may be common if prices and scarcity increase significantly for high-GWP refrigerants. If high-GWP refrigerants remain plentiful, almost no retrofits are expected. The retrofit demand can be modeled using different retrofit rates.

HFC retrofits today include replacing R-404A (GWP 3922) and R-507 (GWP 3985) systems with lower-GWP HFC blends such as R-407A (GWP 2107) or R-407C (GWP 1774), or with HFO-HFC blends including R-448A (GWP 1386) or R-449A (GWP 1396).

Potential reductions from retrofits are inversely proportional to decreases in the HFC supply, that is, the potential reductions from retrofits are greatest when the HFC supply is the highest, because equipment made with very-high GWP refrigerants can change to much lower-GWP refrigerant. As the HFC phase-out continues, additional new equipment will become lower-GWP, and the reductions potential from retrofitting will be available to fewer and fewer remaining old equipment using high-GWP HFCs.

In addition to servicing demand and retrofits, some existing equipment will retire earlier than normal due to the cost or inconvenience of buying or finding high-GWP HFCs. We observe similar practices today as end-users of refrigeration and AC equipment prepare for a total phase-out in new production and import of HCFC-22 in the United States beginning January 1, 2020. Although non-imported, recycled HCFC-22 can be used indefinitely without restrictions, many end-users are proactively preparing for less HCFC-22 in the future by retrofitting or prematurely retiring their HCFC-22-using equipment.

To model reductions under a “Best Case Scenario” with retrofits, we assumed that in addition to all new refrigeration and AC equipment using low-GWP refrigerants (modeled as “Best Case Scenario”), all equipment using HFC refrigerants with a 100-year GWP greater than 2500 would retrofit to using R-407A (GWP 2107), R-407F (GWP 1825), R-448A (GWP 1386), or R-449A (GWP 1396). We use an average refrigerant GWP of 1500 for retrofitted equipment. The following assumptions and emissions factors were used:

From data reported to the CARB Refrigerant Management Program, we estimate that in 2016, 37 percent of equipment in the following end-use categories uses either R-404A or R-507 as the refrigerants, with 100-year GWPs of 3922 and 3985, respectively (in the list below, lbs. refers to equipment’s refrigerant charge size):

- Centralized system large 2,000-lbs.+
- Centralized system medium 200-2,000 lbs.
- Cold storage large 2,000-lbs.+

- Cold storage medium 200-2,000 lbs.
- Process cooling large 2,000-lbs.+
- Refrigerated condensing units small (50-200 lbs.)
- Refrigerated condensing units less than 50 lbs.

We assume that beginning January 1, 2017 no new equipment larger than 50 pounds of charge size used for retail food is manufactured with refrigerants having a GWP > 2500 due to U.S. EPA SNAP Program rules, and that existing equipment retires at a normal rate of 1/average lifetime, where average lifetime is 20 years for all categories listed above with the exception of 15 years for the centralized systems.

We then project the number of units in each end-use category that are still using R-404A or R-507 in 2020, the first year we assume retrofits will begin. Numbers of units in use in California for a given year are estimated from RMP data and other data sources as indicated in Appendix A, “Summary of Methodology to Estimate Business-as-Usual HFC Emissions in California” and detailed in “ARB Methodology to Estimate GHG Emissions from ODS Substitutes” (CARB, 2015).

We assume that at the time of equipment retrofit, approximately half of the equipment lifetime remains. RMP data show that more than 90 percent of refrigeration equipment will have at least one leak of 20 percent or more of the charge in the first eight years of equipment life. At the time of the leak, a retrofit would be required if the very-high GWP refrigerant were unavailable. For modeling purposes, we assume a transition of 1/8 of the R-404A and R-507 equipment is retrofitted each year until no more remain. The HFO-HFC blends of R-448A and R-449A were specifically designed as “near drop-in” replacements to R-404A and R-507, with only minor changes needed to the equipment to replace refrigerant oil, seals, and valves that are compatible with the new refrigerants (Chemours, 2016; and Honeywell, 2016).

To estimate the difference in $MTCO_2E$ emissions from pre-retrofit to post-retrofit, we change only the refrigerant GWP, and keep the following emissions factors constant: refrigerant charge size in pounds, annual leak rate, and end-of-life loss rate.

Reductions of indirect GHG emissions from less energy used by the new refrigerants were not included in HFC reductions estimates. Energy efficiency gains of up to ten percent would increase GHG reductions another three to eight percent (EERE, 2015).

The following table D1 shows emissions factors used to estimate reductions from retrofits (shown on following page to preserve table continuity).

### Table D1. Potential Reductions from Retrofits Modeled in Best-Case Scenario, Annual Basis

| Sectors Where Retrofits Would Occur | Estimated Units in CA using R-404A or R-507 in 2020 | Units retrofitted each year 2020 - 2028 | Reductions per year per unit ($MTCO_2E$) | Reductions in year 1 of retrofits ($MTCO_2E$)[1] |
|---|---|---|---|---|
| Centralized system large 2,000-lbs.+ | 240 | 30 | 647 | 19,410 |
| Centralized system medium 200-2,000 lbs. | 6,800 | 845 | 191 | 161,395 |
| Cold storage large 2,000-lbs.+ | 45 | 6 | 1,393 | 8,358 |
| Cold storage medium 200-2,000 lbs. | 130 | 16 | 147 | 2,352 |
| Process cooling large 2,000-lbs.+ | 32 | 4 | 403 | 1,612 |
| Refrigerated condensing units small (50-200 lbs.) | 23,800 | 2,970 | 24 | 71,280 |
| Refrigerated condensing units less than 50 lbs. | 96,200 | 12,020 | 6 | 72,120 |
| **Total $MTCO_2E$** | | | | **336,527** |

Table Notes:
1) The emissions shown are per year, and are not shown in aggregated emissions for multiple years of emissions reductions (reductions are counted for each year of the equipment's remaining life).

The following table shows the aggregated (overlapping years) reductions from retrofits from 2020 through 2030. Due to the long equipment lifetime of up to 20 years, and the assumption that half of lifetime remains at the time of retrofit, some retrofit reductions will continue until 2038 (years 2031 to 2038) not shown in summary table below). The following table has converted reductions to million metric tonnes of $CO_2$-equivalents.

**Table D2. Potential Reductions from Retrofits Modeled in Best-Case Scenario, Aggregated (shown in $MMTCO_2E$)**

| **Sectors Where Retrofits Would Occur** | **2020** | **2021** | **2022** | **2023** | **2024** | **2025** | **2026** | **2027** | **2028** | **2029** | **2030** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Centralized system large 2,000-lbs.+ | 0.02 | 0.04 | 0.06 | 0.08 | 0.10 | 0.12 | 0.14 | 0.14 | 0.14 | 0.14 | 0.12 |
| Centralized system medium 200-2,000 lbs. | 0.16 | 0.32 | 0.49 | 0.65 | 0.81 | 0.97 | 1.13 | 1.13 | 1.13 | 1.13 | 0.97 |
| Cold storage large 2,000-lbs.+ | 0.01 | 0.02 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.06 | 0.07 | 0.08 | 0.07 |
| Cold storage medium 200-2,000 lbs. | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Process cooling large 2,000-lbs.+ | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 |
| Refrigerated condensing units small (50-200 lbs.) | 0.07 | 0.14 | 0.21 | 0.28 | 0.35 | 0.43 | 0.50 | 0.57 | 0.64 | 0.71 | 0.64 |
| Refrigerated condensing units less than 50 lbs. | 0.07 | 0.15 | 0.22 | 0.29 | 0.37 | 0.44 | 0.51 | 0.59 | 0.66 | 0.73 | 0.66 |
| **Total $MMTCO_2E$** | **0.34** | **0.67** | **1.01** | **1.35** | **1.69** | **2.02** | **2.36** | **2.52** | **2.67** | **2.83** | **2.49** |

Impact of changes in refrigerant charge sizes, annual leak rates, and end-of-life refrigerant management:

The methodology described in this document assumes that the Kigali HFC Phase-down Amendment will have no impact on refrigerant charge sizes, annual leak rates, and end-of-life refrigerant management. However, the phase-down is very likely to increase the price of HFC refrigerants, which may have the following impacts that will reduce HFC emissions:

- Accelerate the trend away from single large centralized systems to multiple distributed systems with smaller charge sizes, which tend to leak less because of less refrigerant piping.
- Incentivize the prompt repair of refrigerant leaks to avoid unnecessary refrigerant purchases.
- Incentivize the recovery and proper recycling of valuable refrigerant at equipment end-of-life.

The impacts described above have not been estimated quantitatively in this model for the best and the worst-case scenarios, largely due to lack of certainty or predictability of future charge sizes, leak rates, and end-of-life refrigerant management. However, the historical ODS emissions reductions curves (applied to HFCs) inherently incorporate all changes to charge size, leak rates, and equipment end-of-life refrigerant management.

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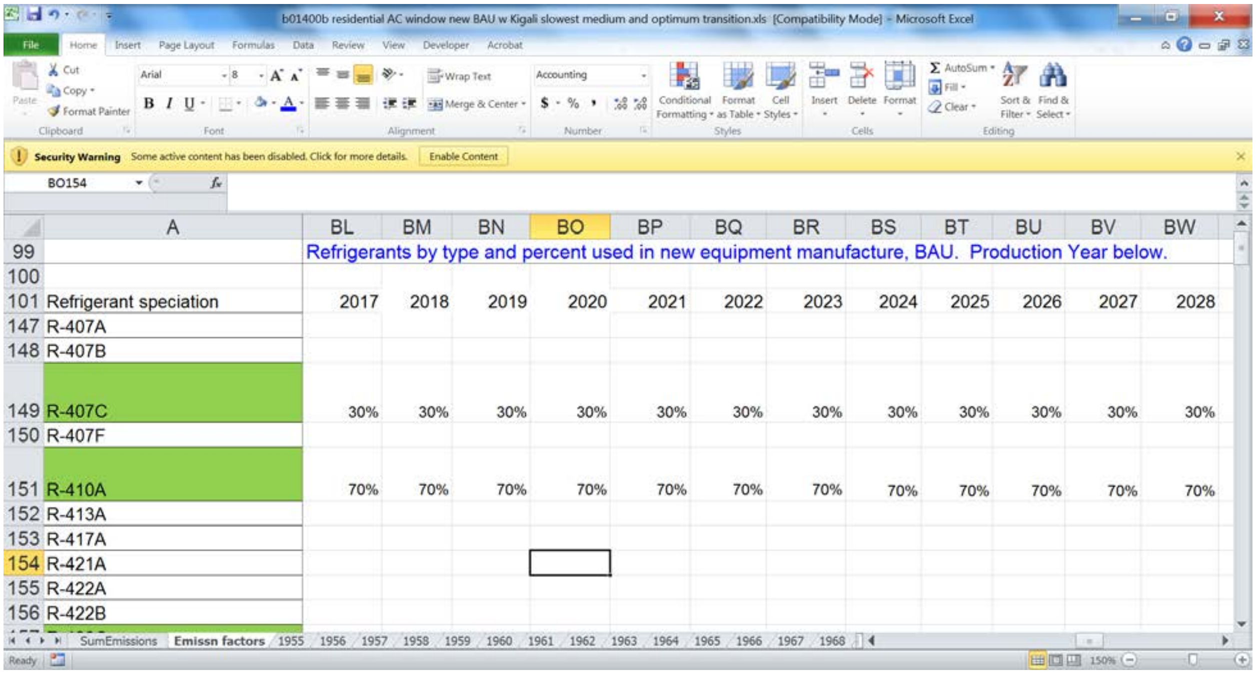
## Appendix E: Example of “Worst Case” Emissions Reductions Scenario

<u>Example using Residential Window AC Units</u>:

Here are the assumed types of refrigerants used in new production years (vintages) for this sector:



b01400b residential AC window new BAU w Kigali slowest medium and optimum transition.xls [Compatibility Mode] - Microsoft Excel

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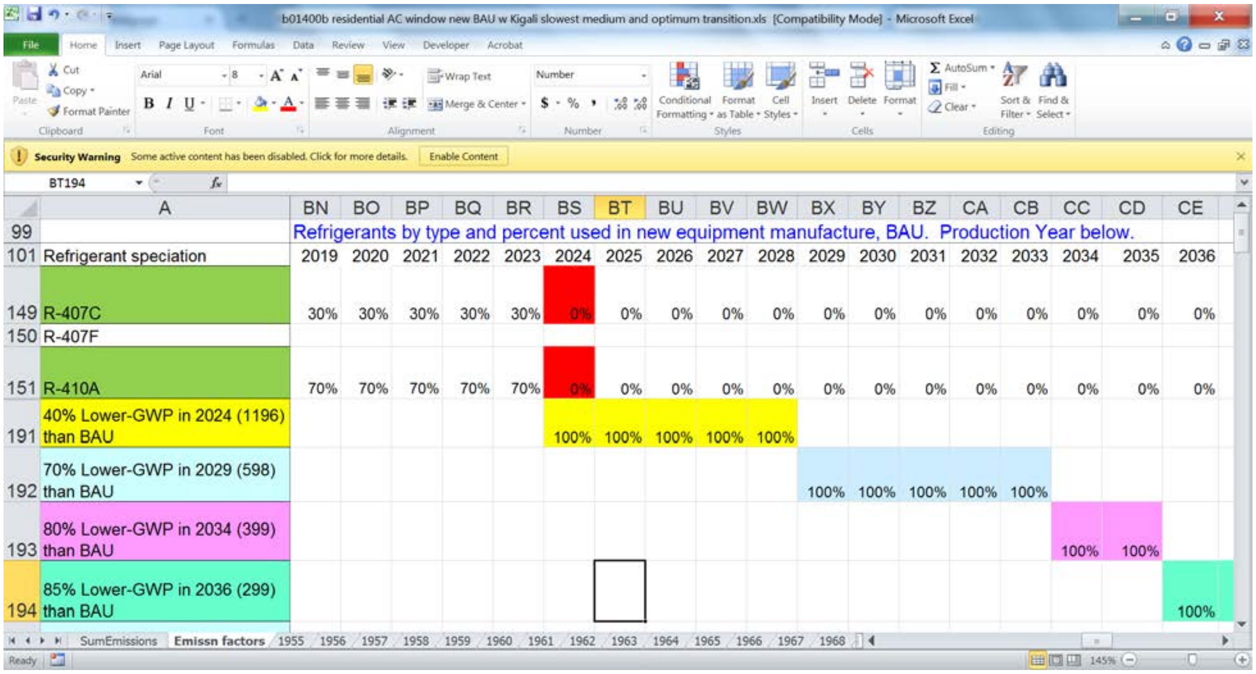
BO154

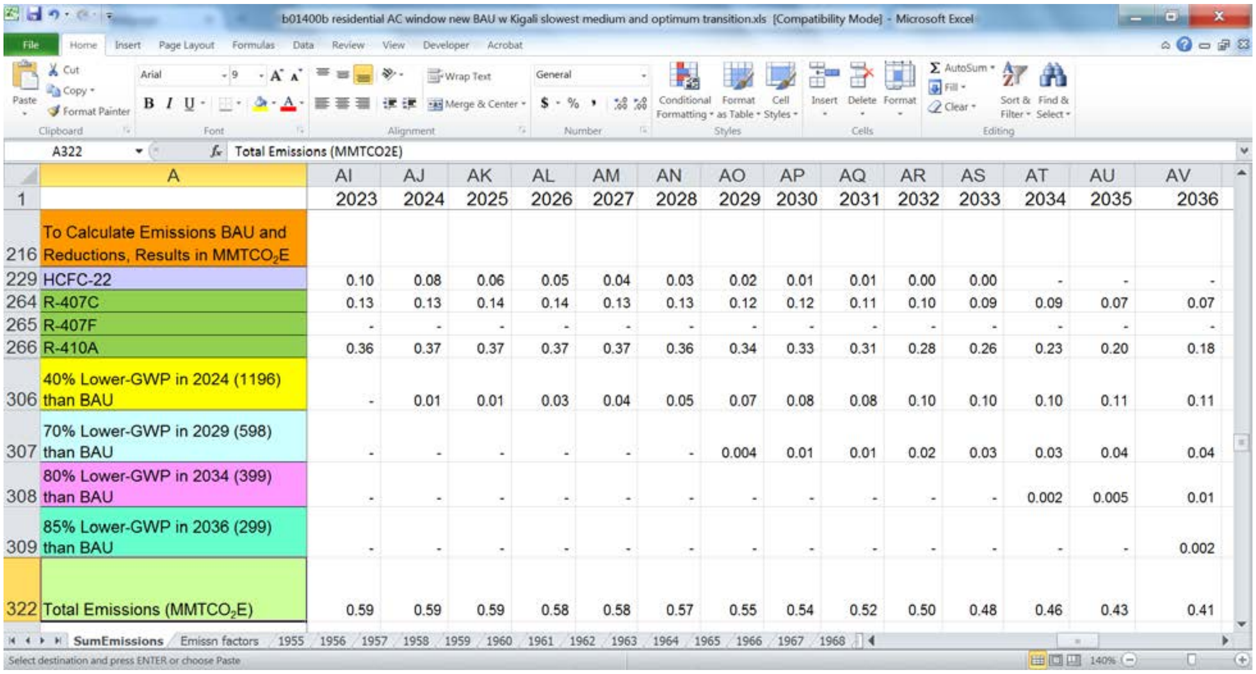
| | A | BL | BM | BN | BO | BP | BQ | BR | BS | BT | BU | BV | BW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 99 | | Refrigerants by type and percent used in new equipment manufacture, BAU. Production Year below. | | | | | | | | | | | |
| 100 | | | | | | | | | | | | | |
| 101 | Refrigerant speciation | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 |
| 147 | R-407A | | | | | | | | | | | | |
| 148 | R-407B | | | | | | | | | | | | |
| 149 | R-407C | 30% | 30% | 30% | 30% | 30% | 30% | 30% | 30% | 30% | 30% | 30% | 30% |
| 150 | R-407F | | | | | | | | | | | | |
| 151 | R-410A | 70% | 70% | 70% | 70% | 70% | 70% | 70% | 70% | 70% | 70% | 70% | 70% |
| 152 | R-413A | | | | | | | | | | | | |
| 153 | R-417A | | | | | | | | | | | | |
| 154 | R-421A | | | | | | | | | | | | |
| 155 | R-422A | | | | | | | | | | | | |
| 156 | R-422B | | | | | | | | | | | | |

Now we model the sector using lower-GWP refrigerants reflecting the lower-GWP value or “warming intensity” of refrigerants due to the HFC phase-down. Note that due to the very high levels of available high-GWP HFCs throughout the first 10% phase-down step of 2019 through 2023, no changes to the GWP values of the available supply of new HFCs were applied until the second phase-down step beginning in 2024.



| | A | BN | BO | BP | BQ | BR | BS | BT | BU | BV | BW | BX | BY | BZ | CA | CB | CC | CD | CE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 99 | | Refrigerants by type and percent used in new equipment manufacture, BAU. Production Year below. | | | | | | | | | | | | | | | | | |
| 101 | Refrigerant speciation | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 |
| 149 | R-407C | 30% | 30% | 30% | 30% | 30% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| 150 | R-407F | | | | | | | | | | | | | | | | | | |
| 151 | R-410A | 70% | 70% | 70% | 70% | 70% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| 191 | 40% Lower-GWP in 2024 (1196) than BAU | | | | | | 100% | 100% | 100% | 100% | 100% | | | | | | | | |
| 192 | 70% Lower-GWP in 2029 (598) than BAU | | | | | | | | | | | 100% | 100% | 100% | 100% | 100% | | | |
| 193 | 80% Lower-GWP in 2034 (399) than BAU | | | | | | | | | | | | | | | | 100% | 100% | |
| 194 | 85% Lower-GWP in 2036 (299) than BAU | | | | | | | | | | | | | | | | | | 100% |

The resulting emissions in MMTCO<sub>2</sub>E were calculated:



Total Emissions (MMTCO2E)

| | A | AI | AJ | AK | AL | AM | AN | AO | AP | AQ | AR | AS | AT | AU | AV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 |
| 216 | To Calculate Emissions BAU and Reductions, Results in MMTCO$_2$E | | | | | | | | | | | | | | |
| 229 | HCFC-22 | 0.10 | 0.08 | 0.06 | 0.05 | 0.04 | 0.03 | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 | - | - | - |
| 264 | R-407C | 0.13 | 0.13 | 0.14 | 0.14 | 0.13 | 0.13 | 0.12 | 0.12 | 0.11 | 0.10 | 0.09 | 0.09 | 0.07 | 0.07 |
| 265 | R-407F | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 266 | R-410A | 0.36 | 0.37 | 0.37 | 0.37 | 0.37 | 0.36 | 0.34 | 0.33 | 0.31 | 0.28 | 0.26 | 0.23 | 0.20 | 0.18 |
| 306 | 40% Lower-GWP in 2024 (1196) than BAU | - | 0.01 | 0.01 | 0.03 | 0.04 | 0.05 | 0.07 | 0.08 | 0.08 | 0.10 | 0.10 | 0.10 | 0.11 | 0.11 |
| 307 | 70% Lower-GWP in 2029 (598) than BAU | - | - | - | - | - | - | 0.004 | 0.01 | 0.01 | 0.02 | 0.03 | 0.03 | 0.04 | 0.04 |
| 308 | 80% Lower-GWP in 2034 (399) than BAU | - | - | - | - | - | - | - | - | - | - | - | 0.002 | 0.005 | 0.01 |
| 309 | 85% Lower-GWP in 2036 (299) than BAU | - | - | - | - | - | - | - | - | - | - | - | - | - | 0.002 |
| 322 | Total Emissions (MMTCO$_2$E) | 0.59 | 0.59 | 0.59 | 0.58 | 0.58 | 0.57 | 0.55 | 0.54 | 0.52 | 0.50 | 0.48 | 0.46 | 0.43 | 0.41 |

Several observations can be made from modeling the impact of lower-GWP refrigerants used in new equipment due to the phase-down.

- Equipment using older refrigerants continues to emit these high-GWP refrigerants for many years, even decades after the refrigerant has been phased-down or banned. Note that a small percentage of window AC units manufactured to use HCFC-22 (last produced in 2009), will operate for many years and continue to emit HCFC-22 through 2031.

- Although we do not expect the HFC blends R-407C and R-410A to be used in any new production units beginning January 1, 2024; it will take an additional 13 years for their emissions to be reduced 50% by the year 2037.

- For the HFC reductions goal year 2030, total HFC emissions from window AC units decrease from 0.60 (BAU) to 0.53 $MMTCO_2E$, a decrease of only 12% less than BAU.

- The rate of decrease is highly dependent upon the combined effects of the average leak rate, end-of-life loss rate, and equipment lifetime. Equipment with low leak rates and long lifetimes result in slow rates emissions reductions. Highly emissive sectors, such as propellants and solvents would reflect lower-GWP changes immediately.

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## Appendix F: Further Background on the Kigali Baseline

The baseline for the phase-down that will be applied to developed countries is as follows: Average annual HFC usage in $CO_2$-equivalents for years 2011, 2012, and 2013; *plus* the annual average allocation in $CO_2$-equivalents of 15% of the HCFC allocation for the Montreal Protocol baseline year 1989 (UNEP, 2016a). (The HCFC allocation includes 2.8% of the CFC consumption [in ODP-tonnes] in 1989, which must then be converted to $CO_2$-equivalents.)

As of this writing, the U.S. EPA has not yet published the baseline to be used as the initial starting point for the HFC phase-down, because the HFC consumption data for years 2011-2013 are still being confirmed and finalized. Using UNEP and U.S. EPA data, CARB has estimated the baseline for the HFC cap to be approximately 298 $MMTCO_2E$ for the U.S. (UNEP, 2017b; U.S. EPA, 2017a). Industry sources have estimated that the national cap will be approximately 270-300 $MMTCO_2E$, although no official data is yet available for these estimates.

HFC usage and emissions are correlated strongly to population (Barletta, et al., 2013). Therefore, we scale down the HFC cap to California's 12.2% share of the U.S. population, for an estimated cap in California of 36.3 $MMTCO_2E$ (CA DOF, 2016; U.S. Census Bureau, 2016b).

The following table shows the data used to estimate the initial HFC cap (shown on following page to preserve table continuity.)

**Table F1. CARB February 2017 estimates on initial HFC Production/Consumption Cap Baseline for the United States and Scaled to California (all units in MMTCO$_2$E, 100-year GWP values, IPCC AR4).**

| Year and Consumption Type | HFCs[1] | HCFCs + CFCs | Total |
|---|---|---|---|
| 1989 HCFC Allocation Baseline plus 2.8% of CFC allocation. Total CFC + HCFC and then multiply by the 15% that is included in the phase-down cap | | 42 | 42 |
| 2011 HFC bulk net supply (consumption) | 241 | | |
| 2012 HFC bulk net supply (consumption) | 227 | | |
| 2013 HFC bulk net supply (consumption) | 278 | | |
| Total HFC bulk net supply (consumption), 2011-2013 | 746 | | |
| Additional non-reported HFC consumption for 2011-2013 by small importers/exporters (< 25,000 MTCO$_2$E/year); approximately 3% of HFC consumption | 22 | | |
| Adjusted total HFC bulk net supply (consumption), 2011-2013 | 768 | | |
| Average Annual HFC Consumption | 256 | | 256 |
| **Total estimated Cap Baseline, U.S. Estimates** | | | **298** |
| **Cap Baseline applied to CA, scale to California's 12.2% share of U.S. population** | | | **36.3** |

Table Notes:
1) HFC consumption data are not yet published by the U.S. EPA, therefore, the estimated baseline shown in this table as it applies to the U.S. and California may need to be adjusted to reflect the values adopted by the U.S. EPA. Non-reported HFC consumption by small distributors/users is a best professional estimate at this time.

## Data Sources and Calculations used to estimate HFC Cap Baseline:

HFCs: The HFC bulk net supply (consumption) data for years 2011-2013 are from the U.S. EPA Greenhouse Gas Reporting Program (GHGRP), "Suppliers of Industrial GHGs and Products Containing GHGs (U.S. EPA, 2017a). Additional non-reported

HFC consumption by small importers/exporters (< 25,000 $MTCO_2E$/year) is estimated to account for approximately 3% of HFC consumption, which is a best professional estimate at this time.

The annual HFC consumption for reported HFCs was 746 $MMTCO_2E$ for 2011-2013, plus another three percent estimated non-reported consumption of 22 $MMTCO_2E$, equaling 768 $MMTCO_2E$ total consumption for the three years, with an average annual consumption of 256 $MMTCO_2E$.

The HCFC and CFC allocation data are from the United Nations Environment Programme (UNEP), Ozone Secretariat Data Access Center (UNEP, 2017b). Data are reported in ozone-depletion potential (ODP)-tonnes. ODP tonnes were converted to $MMTCO_2E$ as follows.

<u>HCFCs</u>: The 1989 consumption of HCFCs in the U.S. was 6,357.1 ODP tonnes, as reported by the UNEP Ozone Secretariat (UNEP, 2017b). The main HCFC used in 1989 is HCFC-22 (comprising 99.9% of all HCFC emissions) with an ODP of 0.055, which converts to 115,584 metric tonnes (simple mass) of HCFCs (6,357.1/.055 = 115,584).

We then convert metric tonnes to $CO_2$-equivalents by multiplying 115,584 metric tonnes by the 100-year GWP of HCFC-22, which is 1810 (IPCC Fourth Assessment, 2007), with 209,206,000 $CO_2$-equivalents, or 209 $MMTCO_2E$.

<u>CFCs</u>: The U.S. allocation of CFCs for 1989 was 317,543 ODP-tonnes (UNEP, 2017b). In 1989, the mix of CFCs used was approximately 1/3 for each of the following: CFC-11 (ODP 1.0), CFC-12 (ODP 1.0), and CFC-113 (ODP 0.8), for an average ODP of 0.93. Metric tonnes by simple mass are 317,543 ODP-tonnes/0.93 average ODP, or 340,225 metric tonnes. The average GWP was calculated as (1/3 * 4750 for CFC-11) + (1/3 * 10900 for CFC-12) + (1/3 * 6130 for CFC-113), equaling 7,253.

Multiplying 340,225 metric tonnes by the average GWP of 7,253 yields 2.468 billion $MTCO_2E$, which is the same as 2,468 $MMTCO_2E$. Applying the 2.8 percent allowance factor results in 69 $MMTCO_2E$ of CFCs.

The next step is to add the HCFC and CFC allowance together and multiply by 15 percent: 0.15 * (209 $MMTCO_2E$ of HCFCs + 69 $MMTCO_2E$ of CFCs) = 42 $MMTCO_2E$.

Adding the HFC amount of 256 $MMTCO_2E$ to the HCFC and CFC amount of 42 $MMTCO_2E$ equals 298 $MMTCO_2E$ national baseline HFC consumption cap. California’s 12.2 percent share of the national population results in a scaled-down amount of 36.3 $MMTCO_2E$ for California (noting that the national consumption cap will be delegated at a nation-wide level and not at the state level).

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## Appendix G: Additionality of HFC Emissions Reductions in California and Potential Leakage of Emissions to Out of State

The following is a short exploration of the impact of California-specific HFC reductions measures, assessing the measurable and permanent GHG reductions above baseline (the additionality) versus the potential leakage of emissions reductions, that is, simply moving the emissions that would have occurred in California to outside the state. This particular exploration is qualitative and does not attempt to quantify actual HFC reductions or leakage in terms of $CO_2$-equivalents, but can be used to inform more detailed economic analyses.

Given the global HFC phase-down schedule of the Kigali Amendment to the Montreal Protocol, we assume that no leakage of HFC emissions will occur in California as a result of the HFC phase-down schedule that the entire United States will follow. However, if California implements HFC reductions measures not required in the rest of the U.S., there is a potential for leakage. High-GWP HFCs not used, and therefore, not emitted, in California could still be used and emitted elsewhere in the United States. Alternately, California-specific HFC regulations could lead to a strong “multiplier effect”, where low-GWP cooling technologies are proven to be technically feasible and cost-effective in California’s multiple climate zones; the low-GWP technologies would then be exported throughout the United States and globally. In this scenario, global HFC reductions would far outweigh any emissions leakage.

Specific HFC reductions measures listed in the Short-Lived Climate Pollutant (SLCP) Strategy adopted by CARB March 23, 2017 are:

Incentive Programs
A financial incentive program in the form of loans or grants would help defray the potential added cost of installing new low-GWP refrigeration equipment or converting existing high-GWP systems to lower-GWP options.

Phase-down in Supply of HFCs
Due to the global HFC phase-down agreement, a California-specific HFC phase-down will not be necessary if the agreement is ratified by the United States in a timely manner.

Prohibition on the Sale of New Refrigerant with Very-High GWPs
This measure would prohibit the sale or distribution of refrigerants with 100-year GWP values of 2500 or greater. Refrigerants that are certified reclaimed or recycled would be exempt from the sales ban. Replacing existing equipment is not necessary, as several refrigerants are currently available with a 100-year GWP of less than 2500 that can be used in existing equipment designed for higher-GWP refrigerants.

High-GWP Refrigerant Prohibitions in New Stationary Systems

This measure would prohibit the use of high-GWP refrigerants in new commercial, industrial, and residential stationary refrigeration and air-conditioning equipment, as follows:

**Table G1. Proposed HFC Reductions Measures in CARB SLCP Strategy.**

| **Stationary Refrigeration or Stationary Air-Conditioning Sector** | **Refrigerants Prohibited in New Equipment with a 100-year GWP Value:** |
|---|---|
| Non-residential refrigeration | 150 or greater, except for small central charge[1] of HFC or HFC-HFO refrigerant (with 100-year GWP no greater than 1500) used in hybrid refrigeration such as secondary loop and cascade systems |
| Air-conditioning (non-residential and residential) | 750 or greater |
| Residential refrigerator-freezers | 150 or greater |

Table notes:
1) No definition currently exists for the equipment referred to as “small central charge” that is used in the text to describe an exception to the 150 GWP threshold for new equipment in proposed HFC reduction measures. The term “small central charge” will be defined during potential rule-making activities in collaboration with end-users of refrigeration and other stakeholders.

We assume that the Kigali Amendment HFC phase-down will be followed as agreed upon by the United States in October 2016, which leaves California with three remaining specific HFC reductions measures recommended in the Short-Lived Climate Pollutant Reduction Strategy (CARB, 2017b):

1. Financial incentive program for early adoption of low-GWP refrigeration equipment, or lower-GWP air-conditioning equipment.
2. Prohibition on the sale of refrigerants with very-high GWP values > 2500.
3. Prohibition on new equipment with high-GWP refrigerants. Refrigerants with a GWP 150 or greater prohibited in new refrigeration equipment, and refrigerants with a GWP of 750 or greater prohibited in new air-conditioning equipment.

The beginning dates for the measures will be developed through an open public and stakeholder rule-making process at a date to be determined.

CARB asserts that the expected HFC emissions reductions from the measures are real, measurable/verifiable, and permanent; in other words, they are additional reductions for the state of California:

Real: GHG reductions by using lower-GWP refrigerants are real because they are chemicals with known properties that are used instead of baseline high-GWP refrigerants. However, in order for this assertion to be true, two caveats need to be addressed: 1) the refrigerant charge size and leak rate of the new lower-GWP refrigerant must not be significantly greater than the high-GWP refrigerant it replaced; and 2) the energy usage of the new refrigerant must not be significantly greater than the high-GWP refrigerant it replaced, or the GHG emissions from electricity usage could be greater than the direct GHG emissions reductions by using a lower-GWP refrigerant. For both caveats, initial CARB analysis indicates it is not likely that new refrigerants would leak more or use more energy than baseline high-GWP refrigerants (ASHRAE, 2015; Danfoss, 2016; DOE, 2015; EIA, 2016; Emerson, 2015; Fritschi, et al., 2016: ORNL, 2016; UNEP, 2016b).

Measurable/Verifiable: The CARB Refrigerant Management Program (RMP) requires all sellers and distributors of high-GWP refrigerant to submit an annual report of the types and amounts (in pounds) of high-GWP refrigerants sold or distributed in California. Annual distribution of refrigerants can be easily compared to past years to assess any trends in the distribution of high-GWP refrigerants. For reference, we assume that all refrigerants sold are used to be added to new equipment, or to replace leaked refrigerant from old equipment. Thus, sales of new refrigerant correlate well to refrigerant emissions once new equipment usage is taken into account.

In addition to the annual distributor reports, the RMP requires an annual report of refrigerant usage from all facilities in California using at least one refrigeration system greater containing more than 200 pounds of high-GWP refrigerant. Although the RMP requirement excludes smaller refrigeration systems and comfort cooling AC, the data collected annually can still be used to measure the trends in high-GWP refrigerant emissions.

CARB also conducts ongoing measurements of the concentrations of HFC-134a and HFC-152a in the atmosphere at the Mount Wilson facility east of Los Angeles, and the air monitoring tower in Walnut Grove (south of Sacramento). Beginning in 2016, additional HFCs were measured at Mount Wilson, including HFC-32, HFC-125, and HFC-143a. The five HFCs currently measured comprise 96 percent of HFC emissions in California, with the remaining four percent HFC emissions from HFC-23, HFC-227ea, HFC-245fa, HFC-365mfc, and HFC-4310-mee (CARB, 2016a).

Permanent: Each refrigeration and AC equipment unit is designed to use a specific refrigerant, which is assumed to be used for the entire equipment lifetime, unless the refrigerant is removed and replaced entirely with a different refrigerant, a process known as a retrofit. Theoretically, it is possible that equipment designed to use low-GWP refrigerants could be retrofitted to use high-GWP refrigerants. However, we have no evidence that this could be done or will be done to stationary refrigeration and AC equipment, given that high-GWP refrigerants will become scarcer due to the Kigali Amendment.

The following example of an exception to the above assumption is included for reference, but it is not a California-specific measure that would lead to HFC reductions leakage:  We are aware of at least one end-use sector, motor-vehicle air-conditioning, where retrofitting from low to high-GWP refrigerant may become a problem with new vehicles using HFO-1234yf (GWP < 10), a low-GWP alternative to HFC-134a for vehicle AC.  Beginning with Model Year 2021 for light-duty motor vehicles (passenger vehicles), HFC-134a will no longer be allowed, and the only approved alternatives at this time are $CO_2$ and HFO-1234yf, with no $CO_2$ air-conditioning planned for U.S. vehicles.

The anticipated problem appears to be the large cost difference between HFC-134a at $7 to $10 per pound retail; compared to the cost of HFO-1234yf, which may be as high as $110 to $160 per pound retail (Sherry and Nolan, et al., 2017).  The large cost discrepancy may create an incentive to recharge HFO-1234yf AC systems with the less costly HFC-134a when replacing leaked refrigerant.  Different recharge fittings between HFC-134a and HFO-1234yf systems, as required by law, may prevent recharging new HFO-1234yf systems with HFC-134a.  Also, as high-GWP HFCs become scarcer, the cost differential should decrease between HFC-134a and HFO-1234yf.

Due to the reasons described above, we have high confidence that the HFC reductions within California will be real, measurable/verifiable, and permanent.  However, the question remains whether or not the reductions will simply be leaked or moved out of California into the rest of the U.S., and if so, is it possible to estimate if the leakage will be significant or not?

## HFC Emissions Leakage from California to Out of State

To address the issue of leakage, we anticipate two opposing forces where each will influence the magnitude of leakage.

<u>High leakage forcing</u> (“un-used HFCs” in California are used out of state).

The HFC reductions measures in California will not affect the total supply of new HFCs to the United States.  Although demand of HFCs in California should decrease, this in turn would lead to an “additional” supply of high-GWP HFCs for the rest of the United States (in the absence of any new HFC reduction measures nationally to complement the Kigali Amendment).  The “un-used” share of California’s HFCs could be simply re-directed and completely used in the other 49 states and eventually emitted, entirely negating HFC reductions in California with a theoretical 100 percent leakage out of state.

In this forcing, we assume that the demand for high-GWP HFCs exceeds supply sufficiently enough to use all the available HFCs as a result of California measures.  We assume that due to the global HFC phase-down, the supply is steadily reduced, which will lead to an increase in price.  If “additional” supply from California’s “share” of national HFC allocations is made available to the rest of the nation, this may stabilize or temporarily decrease HFC prices enough to delay the transition from high-GWP to low-GWP equipment (in the methodology we assume there is a cost premium of up to 10 percent greater initial cost for low-GWP equipment).

If businesses in California buy prohibited or difficult-to-get refrigerants out of state, this out-of-state refrigerant purchasing could lead to higher emissions in California than anticipated under potential HFC reduction measures (that apply to California but not the rest of the United States).

<u>Low leakage forcing</u> (exported low-GWP and emissions reductions technologies are greater than out of state usage of “un-used HFCs”).

In this forcing, the “un-used” HFCs from the California HFC measures are still available to be used elsewhere.  However, the California HFC measures act as multiple “pilot projects” that show the feasibility of low-GWP refrigeration and AC, acting to increase and accelerate the adoption of low-GWP technologies outside the state.  In effect, the emissions reductions technology proven in California will act as a “multiplier effect”, where the technology will be exported to the rest of the United States and around the globe.  With high-ambient temperature climate zones in California, the cooling technologies that work in California may be especially relevant to cooling in developing countries with high ambient temperatures that could “leap-frog” cooling technologies from ODS refrigerants or no cooling at all, and go directly to low-GWP cooling technologies (Shah, et al., 2015).  The resulting reductions outside California could be many times greater than emissions from any “un-used” HFCs due to the California HFC measures.  The multiplier effect will also help other regions and countries in meeting their HFC phase-down commitments.

In order for the low leakage forcing scenario to be more likely than the high leakage scenario, the following assumptions will have to be very likely to occur:

- The initial cost of low-GWP refrigeration and AC equipment, currently estimated to be ten percent or greater than high-GWP HFC equipment, will decrease as more low-GWP equipment is developed and produced, enjoying a larger scale of production which generally results in price decreases per unit.

- The entire lifecycle cost of low-GWP equipment should not be significantly greater than traditional high-GWP HFC equipment, and should be approximately the same after maintenance, refrigerant cost, and energy cost are included in lifecycle cost.

- As high-GWP HFC supplies decrease, the price will increase.  Eventually, perhaps by 2029 with a 70 percent reduction in supply, the price of high-GWP HFCs will be too high to rationalize its use in any new equipment and to meet the servicing demand (replacing leaked refrigerant) in equipment still using high-GWP HFCs.

- The price of natural refrigerants (carbon dioxide, ammonia, and hydrocarbons) will not increase or decrease as a result of the Kigali Amendment or California HFC measures. Currently, the natural refrigerants are a fraction of the cost of HFCs, in part because they cannot be patented by any one company or group of companies, and also because they are very common products or byproducts of other industrial processes.

- The price of hydrofluoro-olefins (HFOs), the newest synthetic fluorinated refrigerant is currently very high, but this price is expected to decrease as HFO production increases to supply the low-GWP substitutes needed to replace HFCs. For example, Honeywell started up a new HFO plant in Louisiana in 2017 and Chemours (formerly DuPont) has broken ground on a new HFO manufacturing plant in Texas that will triple their current production capacity of HFOs. HFO-1234yf is also being produced outside of the United States in China, Japan, and soon in India (Andersen and Seidel, 2015).

- Lower-GWP stationary air-conditioning may only be feasible if the existing safety codes and standards are revised to include refrigerants classified as “A2L”, or non-toxic (A), and slightly flammable (2L). The leading contenders to replace non-toxic and non-flammable (A1) HFC blends for AC are HFC-32, and HFO-HFC blends that are slightly flammable A2L refrigerants. As of December 2017, Underwriters Laboratory (UL) was in the process of conducting safety tests on A2L refrigerants. The results, expected by the end of 2018, will be used to revise current safety codes and standards. Initial results indicate that A2L refrigerants will be allowed in stationary AC, although some safety changes to equipment may have to occur.

- Many refrigeration and AC equipment manufacturers and end-users will adopt low-GWP technologies before a given HFC phase-down step compels them to do so by simple lack of high-GWP refrigerants. Reasons to adopt low-GWP equipment before absolutely necessary may include: 1) Desire to act or appear as an environmentally responsible organization, 2) Desire to avoid State or Federal HFC regulations, 3) Desire to manage for the long-term, fearing higher HFC prices as the cap tightens, and 4) Plans to transition completely away from fluorinated refrigerants, which in many cases, are currently on their third round of phase-outs or phase-downs since the 1990s. Additionally, there is no guarantee that the new HFOs will not be subsequently phased out of production due to unforeseen environmental problems or the exacerbation of predicted problems from HFOs such as their breakdown in the atmosphere to trifluoroacetic acid (TFA), which is deposited in surface waters and can accumulate to levels toxic to aquatic organisms. Modeling has been completed for some, but not all uses of HFOs to determine if future HFO usage could increase TFA concentrations to levels that are harmful to aquatic life (Solomon, et al., 2016; Zhai, et al., 2015).

- Consumers in California will not purchase significant quantities of high-GWP refrigerant or equipment containing such refrigerant outside of state borders.

A third scenario might be possible where although there is negligible leakage of HFC reductions from California, there is also a negligible multiplier effect, effectively reducing HFC emissions to only those occurring within California.

The extent of HFC emissions leakage outside California will be very dependent upon the continued demand for high-GWP HFCs in the rest of the country. If we assume that the demand is extremely high, then leakage is high, perhaps even with significant adoption of low-GWP equipment in the country. For example, refrigeration equipment in the next few years could conceivably resemble a bimodal distribution where the equipment either uses very-low GWP natural refrigerants or near-pure HFOs, or uses very-high GWP refrigerants with GWPs greater than 2000 or 3000. In this scenario, while overall GHG emissions from refrigerants decrease, there is a still a high demand for high-GWP refrigerants.

Alternately, HFO-HFC refrigerant blends with a “mid-level” GWP greater than 150 but less than 1000 could become very prominent, displacing the need for both low-GWP or traditional high-GWP HFCs. In this scenario, the demand for high-GWP refrigerants is low, but overall GHG reductions are also lower than a rapid transition to low-GWP equipment.

In 2010, the European Union (EU) began working on an HFC reduction plan that was formally adopted as the EU F-gas regulation in 2014 and took effect January 1, 2015. The adopted plan is a combination of an HFC phase-down and prohibitions of high-GWP HFCs in new equipment, with a target of 21% remaining $CO_2E$ emissions from HFCs in 2030, compared to the 2015 baseline. Lessons learned from the EU F-gas regulation have informed the F-gas policies of Australia, Japan and Canada, which are each using a different regulatory structure from the one in place in Europe. For example, Australia has drafted plans to move forward with a phase-down only and will use substance bans only as needed to reach goals. Canada is combining a phase-down matching the Kigali amendment with some GWP limits that do not replicate those in the EU F-gas regulation. Japan is still developing its strategy. California is monitoring the progress of the EU F-gas regulation and assessing the success of the different aspects of the regulation.

### Preliminary Conclusions Requiring Additional Analysis

If low-GWP refrigeration and air-conditioning are largely accepted as both cost-effective and technically feasible by the end-users before 2024 (the first significant reduction in HFC supply), then the demand for high-GWP HFCs will be lower than projected business-as-usual, and leakage of HFC reductions from California will be minimal. Conversely, if low-GWP refrigeration and AC is initially rejected or very slow to adoption, then HFC leakage from California could be significant.

If California HFC emissions regulations are adopted and shown to be technically feasible and cost-effective, this will act as a multiplier effect and accelerate the transition from high-GWP to low-GWP refrigeration and air-conditioning equipment worldwide. The HFC emissions reductions outside California would be much greater than any additional emissions from leakage.

CARB believes that the current national and international refrigerant trends point towards a significant adoption of low-GWP technologies in the next five to eight years. If low-GWP technologies are widely adopted, we expect that HFC leakage (from California to outside the state) will be minimal as a result of implementing California-specific HFC reduction measures.

## Appendix H: Supply versus Demand: Initial HFC Supply Cap is Greater than Business-as-Usual (BAU) Demand of HFCs

U.S. EPA Regulations: As designed by the authors of the Kigali Amendment to the Montreal Protocol, the U.S. estimated national baseline cap (i.e., before annual caps such as the 90% in 2019 are applied) of approximately 300 $MMTCO_2E$ is roughly equivalent to expected consumption and demand in 2019 under business-as-usual before 2015 and 2016 changes to U.S. EPA SNAP refrigerant listings. (As shown in Figure H-2, “HFC Consumption vs. Emissions, U.S. 2000-2020”, where we assume consumption is synonymous with supply, which generally equals demand.)

A 10 percent reduction in consumption (supply) beginning 2019 results in a supply of approximately 270 $MMTCO_2E$. Although this supply would appear to be less than anticipated demand, it is not, because the SNAP changes introduced in 2015 and 2016 are expected to reduce the anticipated demand by 10 percent or more below the demand that would have existed prior to 2015 and 2016 SNAP rules.

The SNAP changes (Federal Register, 2015 and 2016) that will affect the demand for HFCs between now and 2023 (the last year of the initial 10 percent phase-down step) are summarized below:

Retail Food Refrigeration, Supermarket Systems: R-404A and R-507 (the standard HFC refrigerants that replaced HCFC-22 in retail food refrigeration), are not allowed in new equipment beginning January 1, 2017. R-404A and R-507 have GWPs of 3922 and 3985, respectively. The most common replacement refrigerants used thus far are R-407A (GWP of 2107), R-448A (GWP of 1386), and R-449A (GWP of 1396). Effectively, the demand for refrigerants used in new retail food equipment in terms of $CO_2$-equivalents is less than half the amount prior to SNAP changes. Low-GWP refrigerants including $CO_2$, ammonia, and propane are also increasingly being used in new supermarket systems.

Household Refrigerator-Freezers: HFC-134a (GWP 1430) is unacceptable in new units beginning 2021. Although refrigerants such as R-450A (GWP 601) and R-513A (GWP 630) are listed as acceptable under SNAP, it is expected that most new appliances will use isobutane (R-600a) with a GWP of 3, as the preferred refrigerant.

Light-duty Motor Vehicle Air-conditioning: HFC-134a is unacceptable in new vehicles beginning Model Year 2021. The current alternatives are HFO-1234yf (GWP < 10), $CO_2$, (GWP of one), and HFC-152a (GWP of 124).

Insulating Foam: All high-GWP HFCs deemed unacceptable, beginning January 1, 2017 for rigid polyurethane boardstock, January 1, 2019 for rigid polyurethane slabstock, and gradually incorporating all types of insulating foam by January 1, 2025. The alternative foam expansion agents used are HFOs (GWP < 10) and $CO_2$ (GWP of one), methyl formate (GWP of 5 or less), and hydrocarbons (GWPs 3 to 10).

Cold Storage Warehouses: Many high-GWP HFCs, including R-404A, R-507, and HFC-134a will be unacceptable in new equipment used in cold storage warehouses beginning January 2023. Potential substitute refrigerants may include R-448A, R-449A, and ammonia (GWP 0).

Aerosol Propellants: Although SNAP rules prohibit HFC-134a in aerosol propellant products beginning 2021 for a wide number of products, CARB analysis of the prohibitions indicate that the prohibitions largely duplicate existing CARB regulations on consumer product aerosols. Therefore, the SNAP rules are not expected to decrease propellant HFC emissions in California beyond State regulations that have been in place since 2012. Metered dose inhalers, or medical dose inhalers (MDIs) are excluded from CARB aerosol propellant regulations, and from SNAP Rules 20 and 21 approved in 2015 and 2016.

Additionally, current SNAP rules (Federal Register, 2016) have listed high-GWP HFCs as unacceptable beginning January 1, 2024 for new centrifugal chillers, new positive displacement chillers, and other end uses. Negligible emissions reductions are expected from these uses before 2024.

To ascertain if the SNAP changes will result in a demand for HFCs even lower than the initial 10 percent reduction in supply will offer, the relative emissions by end-use sector can be used to correlate to relative demand. Note that although demand by mass weight is up to 50-60 percent greater than emissions for a growing chemical sector such as HFCs, the relative emissions are a good correlation to relative demand by sector – we assume that leaked refrigerant will be replaced by the same refrigerant in operating equipment. The following pie chart shows the percent relative weighted emissions by carbon dioxide-equivalents (correlating to relative demand) of HFCs in California in 2016 by end-use sector (emissions are first calculated in carbon dioxide-equivalents).

**Figure H-1. Relative Percent of HFC Emissions by End-Use Sector (CA, 2016) of Total Estimated 19 $MMTCO_2E$ HFC Emissions.**

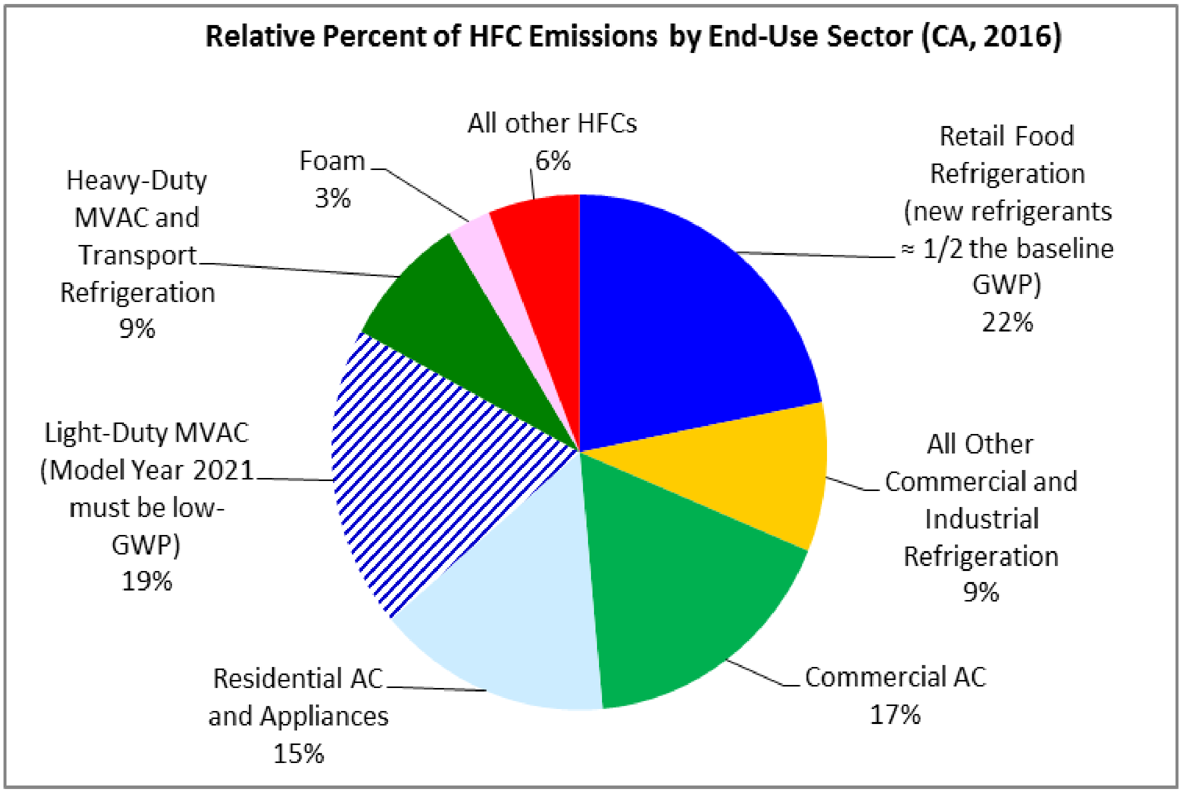


Figure note: "All other HFCs" includes: Consumer product aerosol propellants (3.6 percent), medical dose inhaler aerosol propellants (0.8 percent), solvents (1.4 percent), and fire suppressants (0.2 percent).

The SNAP-affected sectors comprise 44 percent of emissions (22 percent retail food; 19 percent light-duty MVAC, and 3 percent foam). Light-duty MVAC HFC demand will reach near zero, while retail food HFC demand should be approximately half its former value. The relative percent of former HFC demand that will no longer exist for new equipment is 11 percent reduction in retail food (1/2 former baseline of 22 percent) + 19 percent light-duty MVAC + 3 percent foam = 33 percent lower HFC demand.

The new equipment will have a 33 percent lower demand for high-GWP HFCs. However, the servicing demand of existing equipment requiring replacement refrigerant for leaks must also be considered. New HFC supply has two separate demand sectors; the first is for new equipment (and materials), and the second is for replacement refrigerant for existing equipment, known as "servicing demand."

The United Nations Environment Programme (UNEP) estimates that globally, 40 percent of all new HFC production is used in new equipment, and 60 percent is used to service existing equipment (UNEP, 2015). In mature saturated markets with slower growth in new equipment, the servicing demand is more commonly closer to 70 percent of all HFC production, with 30 percent of HFC production used in new equipment and products. Retail food refrigeration and MVAC have servicing demand needs to replace lost refrigerant; insulating foam uses HFCs only at the time of production and has no servicing demand. To account for the 30 percent demand by new equipment and materials, we apply the 30 percent factor to the reduced $CO_2$-equivalents now needed in new retail food refrigeration, light-duty MVAC, and insulating foam. Due to SNAP changes for new equipment, the lower overall HFC demand (in $CO_2$-equivalents) for new equipment and materials would be: 11 percent for new retail food refrigeration equipment (as previously calculated); 19 percent for new light-duty MVAC, and 3 percent for insulating foam; a total of 33 percent lower demand. If we multiply the 33 percent lower demand by the 30 percent share of new HFCs used in new equipment/materials, the HFC demand reduction is 33 percent of 30 percent, equaling 9.9 percent. This can be expressed in the following equation, where reduction means decrease in HFC $CO_2$-equivalents: [(33% reduction of $CO_2$-equivalent demand in new refrigerant equipment, MVAC, and insulating foam * 30% of refrigerant manufactured, which is used for new equipment) = 9.9%].

The 9.9 percent reduction in new demand of HFCs is approximately the same reduction (of demand) as the initial 10 percent reduction in consumption (supply). Therefore, the first 10 percent reduction cap is not expected to result in reductions additional to the business-as-usual scenario (with SNAP regulations included); reductions however would occur when the next cut in consumption occurs. The 40 percent reduction phase-down step beginning in 2024 is the first reduction step that will result in additional emissions reductions.

<u>California CARB Regulations</u>:
In addition to the U.S. EPA regulations that will decrease the demand of HFCs, current CARB regulations will also further decrease the emissions and presumably the demand for HFCs in California. HFC emissions reductions from CARB regulations are expected to decrease emissions three to seven percent by 2020, compared to BAU with no CARB regulations. A brief description of current CARB HFC regulations follows.

Refrigerant Management Program (RMP): Modeled after the U.S. EPA Clean Air Act Section 608 program to protect the stratospheric ozone layer by reducing usage and emissions of ODS, CARB also included non-ODS HFCs with a 100-year global warming potential of 150 or greater (defined as “high-GWP” by the regulation). Global warming potential values are from the 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change. The RMP requires inspections and repairs to avoid leaks in commercial and industrial facilities with large refrigeration systems using more than 50 pounds of high-GWP refrigerant (for example, supermarkets).

Small-can “DIYer” (do-it-yourselfer at-home mechanic) Regulation for Mobile Vehicle AC Re-charging: The regulation to reduce emissions from small containers of automotive refrigerant requires the use of self-sealing valves on containers, improved labeling instructions, a refundable deposit recycling program, and an education program that emphasizes best practices for vehicle recharging.

Semiconductor Manufacturing F-gas Regulations: Regulations for semiconductor manufacturing have set emission standards for operators of semiconductor operations and requires reporting of F-gas use. In addition to HFCs, other very-high-GWP F-gases are included; perfluorocarbons (PFCs) sulfur hexafluoride ($SF_6$), and nitrogen trifluoride ($NF_3$).

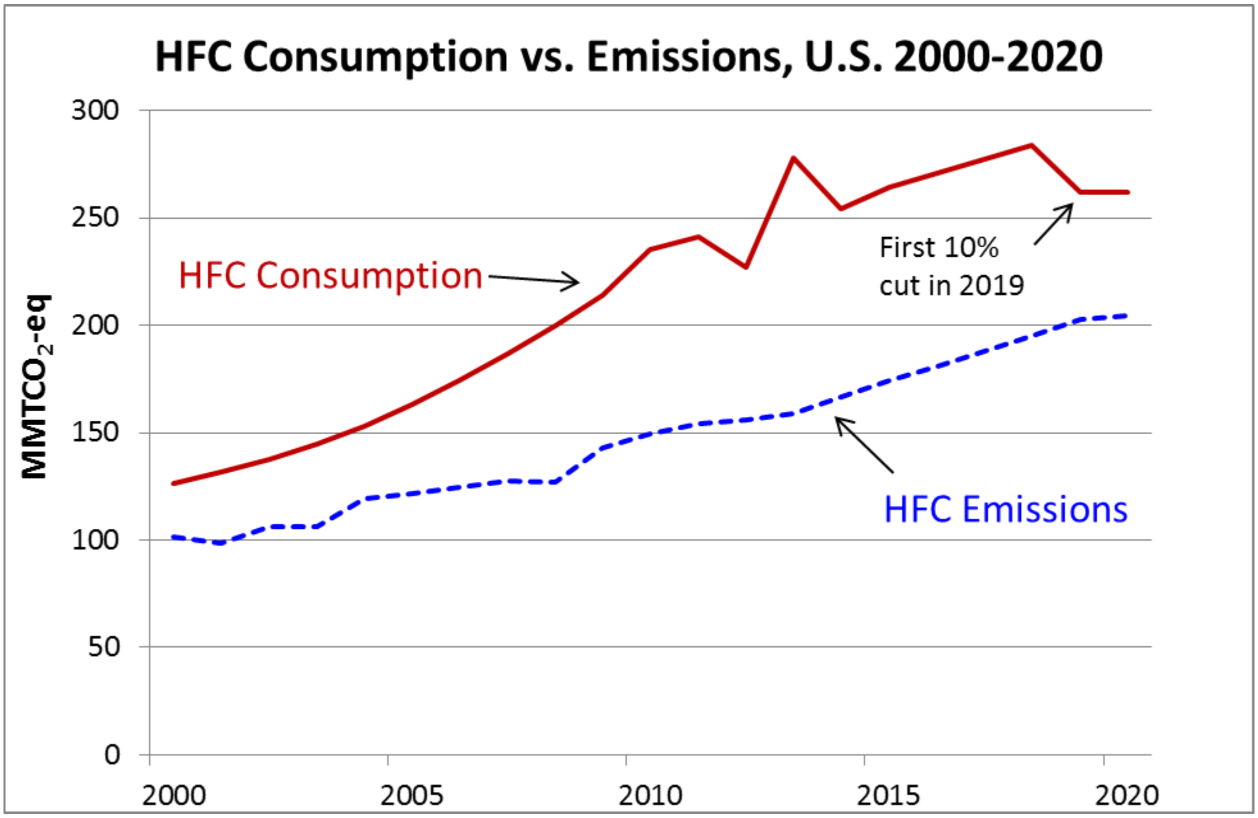
Consumer Product Aerosol Propellant Regulations: Prohibits aerosol propellants with a GWP of 150 or greater used in spray dusters (keyboard dusters), boat horns, tire inflators, and other consumer aerosol products.

Appendix C contains additional details on end-use sectors not likely to be affected by the Kigali Amendment phase-down. Additional information on the impact of HFC emissions by servicing demand and retrofits is in Appendix D.

## The Delay between Consumption and Emissions

Whichever type of refrigerant is examined, a key relationship exists which is essential to modeling: the delay between consumption and emissions. This is seen both for the ODS historical data used in scenarios H1 and H2, and for existing HFC data.

**Figure H-2. HFC Consumption vs. Emissions, United States, 2000-2020.**



Sources of data for Figure H-2: Consumption data for 2000 – 2008 are from voluntarily reported HFC consumption to the U.S. EPA as described in Godwin, 2012. Consumption data for years 2010-2015 are from the mandatory GHG reporting program to the U.S. EPA (U.S. EPA, 2017a). To estimate consumption for 2009, the midpoint between 2008 and 2010 consumption was used. Emissions data for 2000 – 2015 are from the U.S. EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks (U.S. EPA, 2017b). Consumption and emissions for 2016-2020 are estimated using a best-fit regression with the 2019 Kigali consumption cap applied.

The preceding figure shows that thus far, HFC emissions have lagged behind the HFC consumption. Based on trends since the year 2000, we expect HFC emissions to continue to lag behind the consumption schedule.

By 2015 (the most recent year with expert-reviewed and verified data), the consumption of HFCs exceeded emissions by approximately 60 percent. We expect the consumption to exceed emissions as long as the use of HFCs continues to grow (both for new units and to replace ODS such as HCFC-22).

The reason that a time lag exists between a fluorinated gas (F-gas) phase-down and actual reductions is due to the large numbers of equipment and materials that use F-gas refrigerants and compounds that continue to leak or emit F-gases throughout the life of the equipment. This amount of F-gas contained within existing equipment/materials is often called the “bank” of F-gas or the “installed base”. For example, CFC-12 was the refrigerant used in almost all residential refrigerator-freezers through 1995, until its use was prohibited January 1, 1996 in new units by the Montreal Protocol, but many CFC-12 refrigerators still exist and continue to operate.

Although no new refrigerator-freezers using CFC-12 refrigerant (R-12, or Freon®) have been allowed in the United States since 1995, emissions of CFC-12 from older refrigerator-freezers have continued through the present time, more than 20 years after CFC-12 was banned in new equipment. Eventually, all refrigerators using CFC-12 will reach their equipment end-of-life, and CFC-12 emissions will go to zero from this end-use sector. A similar time delay can be applied to any equipment using refrigerants that have been phased-out from new production. The long time it takes for the population of existing equipment to transition from one refrigerant to another is often called “the inertia of the installed base”.

The rate of emissions reductions from the phase-down of CFCs and the ongoing phase-down of HCFCs illustrates that there is an expected and unavoidable delay between a production/consumption phase-down and the intended emissions reductions because of long equipment life times. The relevant issue is that emissions reductions of a phased-down refrigerant will always lag behind the reductions in production/consumption. Estimating the time delay from a production/consumption phase-down to subsequent emissions reductions can be applied from historical data, and is necessary to predict future emissions of HFCs.

## Appendix I: Acronym List and Glossary of Terms

### Acronym List

| | |
|---|---|
| A1 | A non-toxic, non-flammable refrigerant. Almost all CFCs, HCFCs, and HFCs are A1 refrigerants. In the ASHRAE Refrigeration Safety Classification Scheme, "A" is non-toxic and "B" is toxic. The numbers 1, 2, and 3 refer to flammability with 1 non-flammable, 2 slightly flammable, 2L very slightly flammable and 3 highly flammable. |
| A2L | A non-toxic and very slightly flammable refrigerant. Many hydrofluoro-olefins (HFOs) are A2L refrigerants. |
| A3 | A non-toxic and highly flammable refrigerant. Hydrocarbons such as propane (R-290) and isobutane (R-600a) are A3 refrigerants. |
| A5 | Article 5 countries as listed in the Montreal Protocol on Substances That Deplete the Ozone Layer. Article 5 countries are developing nations. Developed countries are often referred to as "non-A5" countries. |
| AC | Air-conditioning |
| ASHRAE | American Society of Heating, Refrigeration, and Air-Conditioning Engineers |
| BAU | Business-as-usual |
| CARB | California Air Resources Board |
| CFC | Chlorofluorocarbon |
| $CO_2$ | Carbon dioxide |
| $CO_2E$ | Carbon dioxide equivalent(s) |
| DIYer | Do-it-yourselfer (at-home mechanic) |
| DOE | United States Department of Energy |
| EMFAC | CARB EMissions FACtor model (vehicle emissions) |
| EOL | End-of-life |
| EPA | United States Environmental Protection Agency |
| F-gas | Fluorinated gas |
| GHG | Greenhouse gas |
| GWP | Global warming potential |
| HCFC | Hydrochlorofluorocarbon |
| HD | Heavy-duty (vehicle) |
| HFC | Hydrofluorocarbon |

| | |
|---|---|
| HFO | Hydrofluoro-olefin (an unsaturated HFC) |
| HTS | Harmonized Tariff Schedule |
| IPCC | Intergovernmental Panel on Climate Change |
| IPCC AR4 | IPCC Fourth Assessment Report (2007) |
| LD | Light-duty (vehicle) |
| MDI | Metered dose inhaler, also medical dose inhaler |
| $MMTCO_2E$ | Million metric tonnes of $CO_2$ equivalents |
| $MTCO_2E$ | Metric tonnes of $CO_2$-equivalents |
| MVAC | Motor vehicle air-conditioning |
| $NF_3$ | Nitrogen trifluoride |
| ODP | Ozone depletion potential |
| ODS | Ozone-depleting substance |
| OFFROAD | CARB Emissions model for off-road vehicles |
| PFC | Perfluorocarbon |
| PFPE | Perfluorinated polyether |
| RAD | (U.S. EPA) Responsible Appliance Disposal Program |
| RMP | (CARB) Refrigerant Management Program |
| SB | (California) Senate Bill |
| $SF_6$ | Sulfur hexafluoride |
| SLCP | Short-lived climate pollutant |
| SNAP | Significant New Alternatives Policy Program (U.S. EPA program to protect the stratospheric ozone layer) |
| $SO_2F_2$ | Sulfuryl fluoride |
| TEAP | Technology and Economic Assessment Panel (of the Montreal Protocol) |
| TEWI | Total Equivalent Warming Impact |
| TFA | Trifluoroacetic acid (additional details in glossary) |
| TRU | Transport refrigerated unit |
| UL | Underwriters Laboratory |
| UNEP | United Nations Environment Programme |
| U.S. EIA | United States Energy Information Agency |

## Glossary of Terms

Annual Leak Rate. Average annual rate of emissions from equipment operation and servicing (expressed as a percentage of the total chemical charge of the equipment). For example, a refrigeration unit containing 100 pounds of refrigerant that leaked 15 pounds of refrigerant during a year had an annual leak rate of 15 percent.

Azeotropic (refrigerant blend). An azeotrope or a constant boiling mixture is a mixture of two or more refrigerants with the same or very similar boiling points, and where the original proportion of components is not changed by distillation or boiling. The vapor of the azeotropic blend has the same proportions of constituents as the un-boiled mixture.

Baseline. Under the Kigali Amendment, the baseline for HFCs is: the average annual production and consumption of all HFCs 2011-2013, plus 15% of baseline production and consumption of hydrochlorofluorocarbons (HCFCs) in 1989 (the HCFC allocation includes 2.8% of the CFC production/consumption in 1989).

Business-as-usual (BAU). BAU emissions in this analysis are those that would have occurred with no Kigali phase-down, and no additional regulatory measures. The context of this analysis includes the baseline and subsequent phase-down steps specified in the Kigali Amendment; the national U.S. EPA regulations; and the unique California context which includes both California-specific regulations and a California-specific F-gas inventory. This context, absent the effect of the Kigali Amendment, is treated as business-as-usual for modeling purposes.

Charge Size. Total quantity by weight, of a specific chemical that represents the full, normal, or optimal operating amount that is used in existing and new equipment. For example, a residential central AC system typically contains 5 to 7 pounds of refrigerant, giving it a charge size of 5 to 7 pounds.

Class I ODS. An ozone-depleting substance (ODS) that has a high ozone-depleting potential (ODP). The Clean Air Act separated ODS into two groups: Class I and Class II. Class I ODS includes chlorofluorocarbons (CFCs), Halons (brominated fire suppressants), carbon tetrachloride, methyl chloroform, methyl bromide, hydrobromofluorocarbons, and chlorobromomethanes. The baseline Class I ODS are CFC-11 and CFC-12, both with an ODP of one. All Class I ODS have an average ODP of 0.1 or greater.

Class II ODS. An ODS with a lower ozone-depleting potential than Class I ODS. All Class II ODS are hydrochlorofluorocarbons (HCFCs). The most common HCFC is HCFC-22, with an ODP of 0.055 compared to an ODP of 1.0 for CFC-11 and CFC-12. All Class II ODS have an average ODP of less than 0.1, with the exception of HCFC-141b with an ODP of 0.11.

Consumption of HFCs. The consumption is the available supply. It is also defined as the production and import of HFCs into a given country, less the amount of exports. In this methodology, the term production/consumption is often used interchangeably with consumption to denote the available supply of HFCs any given year.

End-of-life (equipment). When equipment or materials reach the end of their useful life and are disposed of or converted into scrap metal or materials. At equipment end-of-life, refrigerant emissions occur unless recovery measures take place.

End-of-Life Loss Rate. Average percent of chemical charge amount that is vented to the atmosphere at the end-of-life when equipment is discarded or recycled.

Global Warming Potential. A measure of how much energy the emissions of one ton of a gas will absorb over a given period of time, relative to the emissions of one ton of carbon dioxide.

High Global Warming Potential. As used in this methodology, high global warming potential (high-GWP) means a refrigerant, F-gas, or any compound or blend of compounds that has a 100-year global warming potential value of 150 or greater, as listed in the 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change. The CARB refrigerant management program regulations define high-GWP as follows:

“High-GWP refrigerant” means a compound used as a heat transfer fluid or gas that is: (A) a chlorofluorocarbon, a hydrochlorofluorocarbon, a hydrofluorocarbon, a perfluorocarbon, or any compound or blend of compounds, with a GWP value equal to or greater than 150, or (B) any ozone depleting substance as defined in Title 40 of the Code of Federal Regulations, Part 82, §82.3 (as amended March 10, 2009).

We note that the term “high-GWP” is arbitrary by its very nature – our intent in this methodology is to be consistent with previous definitions of “high-GWP” in CARB rulemaking, and in the EU F-gas regulation. The distinction between high and low-GWP likely arose from the need to identify motor vehicle air-conditioning (MVAC) refrigerants with lower global warming potential. HFC-134a, commonly used in MVAC has a GWP of 1430 which is “high-GWP”, while the potential MVAC refrigerant HFC-152a has a GWP of 124 (“low-GWP”), and pure HFOs used as refrigerants have GWPs of < 10 (“low-GWP”).

“Very high-GWP” is an informal and relative terms that in this methodology, refers to F-gases with a 100-GWP of 2500 or greater.

Harmonized Tariff Schedule. An HS code or HTS code stands for Harmonized System or Harmonized Tariff Schedule. Developed by the World Customs Organization (WCO), the codes are used to classify and define internationally traded goods. Improvements in these codes could help to decrease illegal imports of refrigerants restricted or banned in the U.S.

Hydrofluoro-olefins (HFOs). Hydrofluoro-olefins are unsaturated organic compounds composed of hydrogen, fluorine, and carbon (essentially "unsaturated" HFCs). Typically HFOs have a GWP of < 10. The unsaturated chemical nature of HFOs allows them to break down within weeks when leaked out into the atmosphere, reducing their global warming potential compared to saturated HFCs which have atmospheric lifetimes of one to 260 years.

Kigali Amendment. Agreement by more than 140 countries to phase down the production and consumption of HFCs globally, adopted October 2016 as an amendment to the existing Montreal Protocol on Substances that Deplete the Ozone Layer (see "Montreal Protocol").

Leakage (of emissions): Not to be confused with refrigerant leaks from equipment, "leakage" in the greenhouse gas emissions field is defined by CARB: "A reduction in emissions of greenhouse gases within the state that is offset by an increase in emissions of greenhouse gases outside the state."

Low-GWP. In this methodology, "Low-GWP" means a refrigerant, F-gas, or any compound or blend of compounds that has a 100-year global warming potential value of less than 150, as listed in the 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Common low-GWP refrigerants include HFOs, carbon dioxide, ammonia, and hydrocarbons. Note that low-GWP is a relative term used for this methodology and CARB does not formally define low-GWP.

Lower-GWP. No recognized definition exists for lower-GWP. We use the term "lower-GWP" in this methodology to indicate an F-gas that has a relatively lower GWP than the baseline F-gas used, but would not necessarily be considered low-GWP. For refrigerants used in refrigeration, the term used in the methodology represents F-gases with a GWP less 1500, but greater than 150. For refrigerants used in air-conditioning, the term represents F-gases with a GWP less than 750, but greater than 150.

Montreal Protocol. The Montreal Protocol, first signed in 1987, is the international treaty governing the protection of stratospheric ozone. The Montreal Protocol on Substances That Deplete the Ozone Layer and its amendments control the phase-out of ozone-depleting substance (ODS) production and use.

Natural refrigerant. Natural refrigerants are naturally occurring, non-synthetic substances that can be used as cooling agents in refrigerators and air conditioners. These substances include hydrocarbons (propane, butane, isobutane, and propylene), carbon dioxide, ammonia, water, and air. Note that natural refrigerants can be derived from petrochemicals and industrial processing. All the natural refrigerants listed are considered low-GWP, with GWPs ranging from zero (ammonia, water, air) to one (carbon dioxide), and three to ten (hydrocarbons).

Non-azeotropic, or zeotropic (refrigerant blend). A non-azeotropic mixture is a mixture of components with different boiling points where the original proportion of components is changed by distillation or boiling. The vapor composition of the zeotropic blend has different proportions of constituents as compared to the un-boiled mixture. As a result, as the mixture boils, the phase change from liquid to vapor occurs in a temperature change of several degrees or more (“glide”) rather than at a constant temperature.

Retrofit. The replacement of the refrigerant used in a refrigeration or air-conditioning system with an alternative refrigerant.

Self-contained. For refrigeration systems, often called “stand alone”, and used to describe small refrigeration systems with hermetically sealed refrigeration units that contain all refrigerating components within their structure. For example, a refrigerated vending machine is a self-contained refrigeration system.

Senate Bill (SB) 1383. California Senate Bill 1383, Lara, 2016 “Short-lived climate pollutants: methane emissions: dairy and livestock: organic waste: landfills”. SB 1383 requires a 40 percent reduction in HFC emissions below 2013 levels by the year 2030.

Servicing Demand. The amount of refrigerant required by existing equipment to refill refrigerant lost from leaks.

Trifluoroacetic acid. Trifluoroacetic acid (TFA) is a decomposition byproduct formed when HFC and HFO gases enter the atmosphere and break down. HFO-1234yf produces five to ten times more TFA than HFC-134a. TFA occurs naturally in seawater in low concentration levels averaging 150 ng/L (nanograms per liter) (Scott, et al., 2005). TFA is not believed to be naturally occurring in freshwater (Berg, et al., 2000), (Wujcik, et al., 2009), although the science is not settled on this issue. TFA is a strong acid and toxic to freshwater aquatic life when it is deposited onto surface waters from precipitation. Because there is no know degradation path of TFA in water, increased use and emissions of HFOs could cause TFA to build up to levels toxic to aquatic life. Currently, fresh water TFA concentrations are well below harmful levels, although the potential harm of TFA from HFO use remains an open question.

Transcritical $CO_2$ (refrigeration). Refrigeration using only $CO_2$ as the heat transfer fluid or gas. Transcritical simply means that the refrigerant passes across the critical point of temperature and pressure of a refrigerant from liquid to vapor. In a sub-critical $CO_2$ system, generally referred to as “cascade”, “hybrid”, or “secondary loop”, a secondary cooling system containing liquid $CO_2$ is cooled by a primary refrigeration unit that may use HFCs, ammonia, or other refrigerants. Sub-critical refers to the $CO_2$ remaining in liquid form without crossing the critical point to vapor.

Vintage. The equipment or HFC-containing material that entered into use in a given year. Also called a production year.

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