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Interindustry Forecasting at the University of Maryland

Consumer Cost Impacts of U.S. Ratification of the Kigali Amendment

Report Prepared for the
Air-Conditioning, Heating, & Refrigeration Institute
and the
Alliance for Responsible Atmospheric Policy

November 9, 2018

Final Report

Consumer Cost Impacts of U.S. Ratification of the Kigali Amendment

For more information about the report, please contact:
Douglas S. Meade, Ph.D.
Executive Director
Inforum
(301) 405-4608
meade@econ.umd.edu

Joseph M. Steed, Ph.D.
Principal
JMS Consulting
j.m.steed@me.com

JMS Consulting
in Partnership with:
Inforum
www.inforum.umd.edu

Prepared for:
The Air-Conditioning, Heating, and Refrigeration Institute
2311 Wilson Blvd, Suite 400
Arlington, VA 22201

and

Alliance for Responsible Atmospheric Policy
2111 Wilson Blvd., 8th Floor
Arlington, VA 22201

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Table of Contents

Abbreviations

AHAM	Association of Home Appliance Manufacturers
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ARAP	The Alliance for Responsible Atmospheric Policy
CARB	California Air Resources Board
CFC	Chlorofluorocarbon
EPA	Environmental Protection Agency
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HVACR	Heating, Ventilation, Air-Conditioning, and Refrigeration
INFORUM	Interindustry Forecasting at the University of Maryland
SNAP	Significant New Alternatives Policy (EPA)
UNEP	United Nations Environment Program

List of Tables

List of Figures

Executive Summary

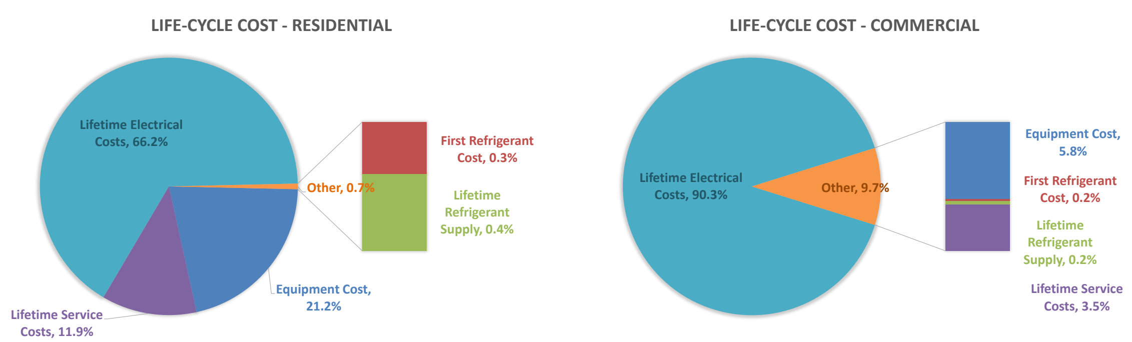
Industries producing and using fluorocarbons play a significant role in the U.S. economy. The broad industry using fluorocarbons as a refrigerant includes the Heating, Ventilation, Air-Conditioning, and Refrigeration (HVACR) industry, along with the related industries: household appliances and motor vehicle air-conditioning. HVACR equipment includes commercial and residential HVACR and commercial refrigeration and is the largest manufacturing industry using fluorocarbons. Insulating foams, medical metered-dose inhalers, aerosols, and several other applications, along with the production of the fluorocarbons themselves, comprise the rest of the broad fluorocarbon-based U.S. industry. Together these industries and their contractor, service, and distribution networks provide 589,000 direct jobs in the U.S. The HVACR and fluorocarbon technologies used globally today are signature American technologies.

U.S. industry supports ratification of the Kigali Amendment to the Montreal Protocol, followed by domestic implementation. The Kigali Amendment provides a global platform for gradual introduction and commercialization of next generation technologies in the U.S. and in the rapidly expanding global market. Prior transitions under the Montreal Protocol enabled these important U.S. industries to maintain their technology leadership. The new Kigali Amendment, which creates a clear path toward global adoption of the next generation technologies, will have a similar effect.

Previous economic analysis indicates that U.S. implementation of the Kigali Amendment is good for American jobs. It will both strengthen America's exports and weaken the market for imported products. Finally, it will enable U.S. technology to continue its world leadership role. The demonstrated benefits to industry are driven by additional equipment exports and domestic replacement of equipment imports, not higher prices for American consumers.

This report presents analysis of the impacts on consumers. It looks in detail at the costs faced by consumers of new equipment in two of the largest manufacturing segments in the industry, residential and commercial air conditioning. For a nominal purchase ten years from now, the various contributions to the consumers' total costs of ownership are examined See Figure ES.1. Energy consumption is the dominant contribution, 66% of lifetime cost for residential air conditioning and 90% for commercial. Refrigerant costs over the lifetime are only 0.7% of lifetime costs for residential and 0.4% for commercial.

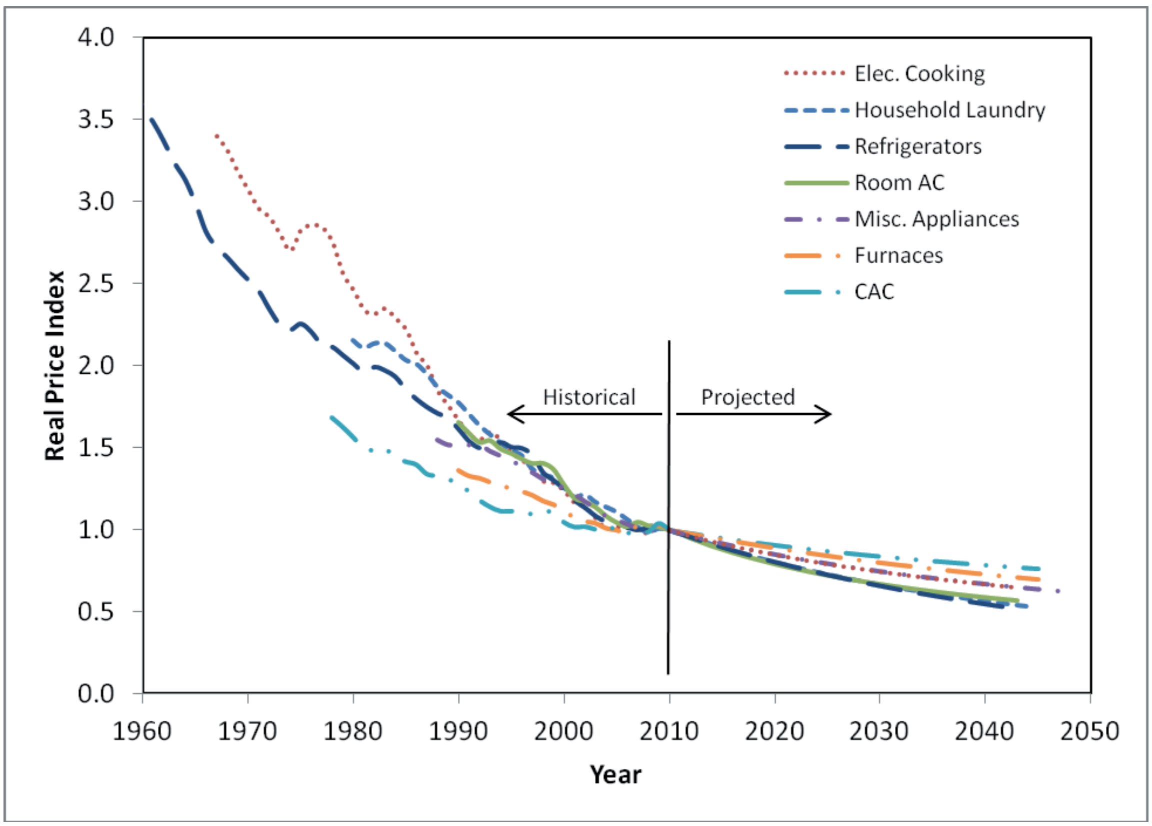
Figure ES.1: Lifetime Cost Breakdown: 2.5-Ton Residential & 15 Ton Commercial Units, 2019



With reasonable expectations about the development of the market, in scenarios assuming U.S. ratification of Kigali compared to assuming no adoption in the U.S., total lifetime ownership costs are very similar, with consumer savings in the 'with Kigali' case. Although there is no reason to expect that refrigerant prices will behave differently during the Kigali transition than during the two previous transitions away from ozone-depleting substances, even assuming a five-times higher price for replacement refrigerants would not significantly change the impact on consumers.

The consumer savings identified in this report cover only two of the largest industry segments. There are over 60 use segments that could be analyzed using more detailed models, such as EPA's Vintaging Model, as a basis. There are likely benefits elsewhere in HVACR as well as in other industries. A qualitative review of several smaller manufacturing segments supports the expectation of at least small consumer savings in several applications. For several segments there is also an underlying trend of reduced real consumer prices over time through previous transitions. Figure ES.2 shows real price indices for refrigerators, room AC, and residential central AC (CAC) along with other appliance categories.

Figure ES.2: Historical & Projected Real Price Indices for U.S. Major Appliance Categories



Ratification and implementation of the Kigali Amendment in the U.S. allows American industries to continue their history of global technology leadership, encouraging domestic production investments, without an increased cost to the consumer. Furthermore, this study shows that some of the largest industrial users of fluorocarbons, particularly residential and commercial air conditioning, will see savings from timely implementation.

Background on the Kigali Amendment

The Kigali Amendment to the Montreal Protocol was agreed upon at a meeting of more than 170 countries in October 2016. It has since been ratified by a sufficient number of countries to enter into effect globally on January 1, 2019, but it has not yet been ratified by the U.S. The fifty-eight countries that have ratified to date include all other major developed country economies. The agreement establishes timetables for all developed and developing countries to freeze and then to reduce their production and use of HFCs, chemicals that are used widely by the U.S. and global industries. HFCs will be phased down over time for most uses, and they will be replaced with new and existing chemicals and products that are more sustainable, while maintaining high energy efficiency. However, countries will also continue to look to the U.S. for policy and technology leadership in the transition.

Under the Montreal Protocol, the global fluorocarbon-using industries have undergone two prior transitions. In each case, U.S. industries were able to use their technological strengths to play a major role in defining the new generation technologies. New technology and manufacturing investments were made in the U.S., and U.S. manufacturers led the way as the world moved toward these new technologies. The transitions have been defined in such a way that older equipment can continue to be serviced with existing refrigerants and need not be replaced before the end of its useful life, minimizing consumer impact. Kigali adopts the same phased approach with long-term goals.

The Montreal Protocol is recognized as perhaps the most successful global agreement of any kind. It has also been good for the U.S. economy, providing certainty to businesses optimizing global investments and benefits to consumers. The Kigali Amendment will continue this economically beneficial effect.

Key Findings

Next Generation Products

- The suppliers of refrigerants and other materials are preparing to supply the materials needed for the Kigali transition in the U.S. Some full-scale manufacturing facilities are in operation in the U.S., and the industry is prepared to expand to serve growth, both domestically and internationally.
- The average market prices of refrigerants and other new materials are not expected to change significantly in real dollars during Kigali implementation, if Kigali is ratified in a timely manner.
- Timely U.S. ratification of the Kigali Amendment provides the smoothest, least costly transition, especially because it would then happen in concert with the rest of the developed countries and rapidly growing markets in developing countries.

Industry Response to Kigali

- Manufacturers in most applications have options to move methodically to Kigali-compliant products, with a range of alternatives to HFCs, including some which

are less costly. Many have already begun the transition, but some changes require modified standards and codes to address flammability.
- Especially in the HVACR segment, U.S. businesses expect to participate in global post-Kigali markets irrespective of U.S. action on Kigali.
- Consistent with Department of Energy mandates, air conditioning equipment designed for sale in the U.S. in 2029, regardless of refrigerant choice, will be more energy efficient than today's equipment. However, consistent with other modeling studies of the transition, the average equipment sold in the 'with Kigali' scenario is assumed to be 1.3% more energy efficient on average than the equipment in the 'without Kigali' scenario.
- Because efficiency standards can place upward pressure on equipment prices, manufacturers must constantly innovate in technology, sourcing, and other areas to minimize those impacts. By coordinating design cycles for refrigerant replacement and efficiency standards, industry can minimize impacts overall.
- Although Kigali-compliant equipment will be manufactured in both scenarios, U.S. manufacturers will locate operations in the near term to support growth of the most promising markets. With Kigali, new facilities are likely to be concentrated in the U.S. Without Kigali, however, the U.S. market for next generation products is likely to grow more slowly, and offshore locations will be favored, also adding freight costs to products shipped back to the U.S. for sale.
- Without Kigali ratification, the U.S. market could become more fractured if states or localities enact non-uniform regulations with varying requirements. The resulting regulatory uncertainty would hinder the development of economies of scale, complicate development cycles, and possibly impact costs. Kigali ratification in the U.S. would eliminate the need for state action and would provide more certainty for planning, avoiding these problems.

HVACR Consumer Cost Elements

- With or without Kigali, consumers in all sectors can continue to use existing equipment throughout its useful life. If implementation of the Kigali amendment is managed properly, consumer access to refrigerant for servicing existing equipment could maintained in a cost-effective manner. Demand would be met by a combination of virgin and reclaimed refrigerants as occurred during previous transitions. Assuming effective refrigerant management approaches, there is no reason to expect a significant cost impact due to Kigali.
- The potential for consumer impact is greatest when equipment reaches the end of its useful life and it is time to purchase new equipment. By continually innovating and balancing cost considerations during design, the initial cost (in constant dollars) of HVACR equipment, refrigerators, room air conditioners and other HFC applications can be minimized substantially, while energy efficiency increases.
- Many industry participants anticipate that equipment prices will remain constant in real terms. Ongoing design cycles are built into product pricing, and there is no information to indicate that designing for Kigali will be more costly than previous design cycles and previous transitions. However, to address unforeseen issues in redesign for Kigali-compliant refrigerants, the analysis instead uses a conservative estimate that the average equipment with Kigali is 10% more expensive than equipment sold in the 'without Kigali' scenario.
- Energy efficiency in HVACR, driven by stepwise government requirements, is expected to improve by the equivalent of about 1.5% per year over the next decade regardless of Kigali implementation.

- Considering the range of refrigerants expected to be in use, the average refrigerant charge size is assumed to be 6.7% smaller for the low-GWP refrigerants and equipment used in compliance with Kigali than for the range of refrigerants and equipment in use without Kigali.
- The industry has an ongoing trend toward reduced refrigerant leak rate in residential and commercial air conditioning and refrigeration products. Leaks and recharging over the lifetime of air conditioning equipment without Kigali are estimated for this study to be equivalent to a leak rate of 10% per year. There is additional incentive to lower significantly the leak rate of flammable and low flammability low-GWP refrigerants, with the improvements applied to all equipment. The average leak rate is assumed here to be approximately 5% with Kigali, reducing consumer recharging costs.
- Maintenance and service fees are expected to be similar with and without Kigali, but average annual costs for the analysis are reduced by 13% for the 'with Kigali' case, reflecting less frequent servicing to recharge lower-leak-rate equipment.
- Refrigerant prices in the air conditioning industry without Kigali are expected to remain constant and are estimated, considering a weighted average of refrigerants in use, to be about $7/lb. Implementation of Kigali would change the mix of refrigerants over time, with initial higher prices for low-volume products but later declines with further growth, combined with growing use where feasible of refrigerants costing much less than HFCs. The average price with Kigali is expected to stabilize over the next decade to at most a slight increase over today's average prices, in real dollars.
- Implementation of similar rules, but rapidly and without Kigali's attention to coordinated phasing in of changes, can create market chaos as seen to some extent under European Union F-gas rules, raising prices, obsoleting existing equipment, and not allowing time for the innovation that has kept costs down in previous transitions.

Air Conditioning Total Cost of Ownership

- For both residential and commercial air conditioning, the total cost of ownership is dominated by energy consumption, approximately 66% of the cumulative total for residential, and almost 90% for commercial.
- Equipment cost is over 20% of the total for residential air conditioning, but under 7% for commercial.
- Maintenance costs are about 12% of the total ownership cost for residential and less than 4% for commercial air conditioning
- The cost of refrigerant, over the lifetime of the equipment, is a very minor component, less than 0.75% of total cost of ownership for a residential unit and less than 0.5% for a commercial unit.
- Life time cost of ownership are shown in the Figures ES.3 and ES.4 for residential and commercial air conditioning with and without Kigali implementation in the U.S. In both cases, energy savings dominate all other costs for a reduced cost of ownership with Kigali.

Figure ES.3: Residential Air Conditioning Total Cost of Ownership for 2029

	Total	Annual Average
Without Kigali	**$17,966**	$1,197.74
With Kigali	**$17,869**	$1,191.29

Figure ES.4: Commercial Air Conditioning Total Cost of Ownership for 2029

	Total	Annual Average
Without Kigali	$393,035	$26,202.34
With Kigali	$388,340	$25,889.34

- Both costs of ownership are relatively insensitive to refrigerant price. Although all assessments of price fail to suggest the average price might be higher, the cost of ownership calculations were repeated assuming average refrigerant prices were five times higher with Kigali. For residential air conditioning the small benefit became an equally small cost. For commercial, the 'with Kigali' scenario still showed a consumer benefit.

Costs in Other Applications

- Applications within the HVACR industry all share the characteristics described for residential and commercial air conditioning. Refrigerant costs are a minor component of total ownership cost over the lifetime of the equipment. For some applications, low-cost refrigerants play an increasing role in Kigali compliance, but must be balanced against other design factors that can add to design costs. Reduced charge size and increased efficiency of next generation refrigerants can help minimize the increase in commodity metals costs otherwise required to achieve efficiency targets. There is little or no reason to expect an increased long-term cost to consumers.
- Home refrigerators are in the process of being converted to low-cost refrigerants today, again for a net improvement in costs. Even before conversion, the refrigerant content represents less than $2 of the total cost of the appliance.
- The foam insulation in refrigerators is also being converted to next-generation blowing agents while maintaining or improving insulating capability, with little overall cost impact.
- Window air conditioners and motor vehicle air conditioners also share the same characteristics and are expected to continue their long-term downward trend in constant dollar pricing.
- The energy savings provided by foam insulation far outweighs its cost, which is only a fraction of the total cost of insulating buildings and refrigerators.
- The reduced leak rate and charge size of next generation equipment in the 'with Kigali' case will reduce the frequency of refrigerant replacement, reducing both the cost of refrigerant needed and the number of service calls required.
- For all applications, next-generation materials are expected to deliver equivalent or better performance at equal or lower total cost of ownership.

1 Introduction

The Montreal Protocol is an international treaty designed to protect the ozone layer. Taking effect in 1989, the agreement required the phase-out of chlorofluorocarbons (CFCs) and, eventually, hydrochlorofluorocarbons (HCFCs). Hydrofluorocarbons (HFCs) were originally introduced in order to achieve a rapid response as a replacement for ozone-depleting substances. In subsequent years, however, the science and technology communities shared concerns regarding the potential impacts of HFCs on the atmosphere and expressed the desire to replace them with next generation technologies.

On October 15, 2016, representatives from more than 170 countries met in Kigali, Rwanda, to develop the Kigali Amendment to the Montreal Protocol. The aim of the Amendment is to reduce worldwide use of HFCs. Under the agreement, developed countries would begin reducing their use of HFCs by 2019, while developing countries would start their reductions by 2024. The goal is to reduce use of HFCs by 85 percent by 2047 and replace them with low-GWP technologies, including hydrofluoroolefins (HFOs), which have far less impact on the atmosphere.

This Amendment is subject to Senate ratification in the U.S. but will formally take effect globally on January 1, 2019 whether or not the U.S. ratifies. Fifty-eight countries have now ratified the Kigali Amendment, including all major developed country economies other than the U.S. A list of ratifying countries is included in Appendix A.1. Specified controlled substances under Kigali are listed in Appendix A.2.

The previous industry-wide transition from CFCs to HFCs resulted in a 90 percent reduction of global warming potential (GWP). Replacing HFCs with next generation technologies such as HFOs, HFC blends, and other choices is expected to reduce global warming potential by an additional 90 percent.[1] Although the environmental goals of the Kigali Amendment are clear, policymakers in the U.S. would like to understand better the economic consequences of Kigali ratification, both the health of the industries employing HFCs in their current products and the costs or benefits to U.S. consumers.

Historical experience through the previous transitions under the Montreal Protocol proceeded smoothly with costs to customers benefitting in many segments from reduced initial equipment price or energy efficiency over the life of the equipment.[2]

1.1 Study Objectives

A previous study[3] by this report's authors examined the current economic contribution of the fluorocarbon, HVACR, and related industries to the U.S. economy and projected how these industries may change over a 10-year or longer period, with and without Kigali ratification. The benefits to American industry in terms of job creation and balance of trade clearly favor ratification of the Kigali amendment.

The current study extends that work to examine the implications for U.S. consumer costs, with two main objectives:

[1] UNEP (2017).
[2] The Alliance for Responsible Atmospheric Policy (2018).
[3] INFORUM and JMS Consulting (2018).

1. Examine in detail the lifetime operating costs for two of the largest HFC-using applications, residential and commercial air conditioning. Specifically, understand the impact on consumers of changes in equipment and refrigerants expected in the two cases: a) with U.S. ratification of Kigali and b) without U.S. ratification of Kigali.
2. Assess, at a high level, the likely consumer impacts of expected changes in other HFC-using industry segments.

The approach is to consider how consumer choices are affected by industry's responses to Kigali and the corresponding impact on consumer costs.

1.2 Background

The current study examines expected changes in consumer costs resulting from Kigali ratification. The focus is on two of the largest air conditioning segments with the greatest direct connection to the consumer, which are also among the largest uses of HFCs. The full range of industry segments and sub-segments includes over 60 segments, each with unique opportunities for additional consumer savings. In addition to the authors' own experience in the industry and in economic analysis, information was gathered from the industry via questionnaire and subsequent interviews. Some of the factors used in the analysis are based on very detailed analyses done by the California Air Resources Board[4].

JMS Consulting has extensive experience in working with the chemicals and HVACR industries. A study completed in 2013[5] provided an earlier analysis of the economic impact of the network of industries related to fluorocarbon production.

Inforum specializes in input-output and industry modeling at the national and regional levels, and also has extensive experience in international trade analysis. Inforum maintains a large database of bilateral imports and exports by Harmonized System (HS) 4-digit products, which is used for the Inforum bilateral trade model of the largest world economies. Inforum recently worked with the Center for Manufacturing Research of the National Association of Manufacturers to complete an industry analysis at the national and regional level for the Air-Conditioning, Heating, & Refrigeration Institute (AHRI).[6]

1.3 Consumer Choices; Consumer Impacts

Consumer choices and the cost impacts of those choices both influence industry actions and are dependent on the business-driven decisions made by industry. In section 2, the expected actions by industry, globally, are first compared for the 'with Kigali' and 'without Kigali' scenarios and are then used to define the market choices available to consumers.

Section 3 then examines the market from a consumer's viewpoint to compare the situations faced by a nominal consumer in 2029, with and without Kigali. It examines the lifetime costs of ownership for both residential and commercial air conditioning. It then considers other potential impacts in the remaining smaller markets.

[4] California Air Resources Board (2017).
[5] Steed (2013).
[6] Center for Manufacturing Research and Inforum (2017).

2 Market Implications of Kigali Ratification

To understand the impact of Kigali ratification on U.S. consumer costs, it's essential to understand what choices the consumer will have based on actions being taken now and over the next few years by U.S. industry. Those actions are likely to vary based on the U.S. government's decision on Kigali, as demonstrated in our earlier work. With an understanding of how the offerings available in the U.S. market would shift, the consumers' decisions within that market can be examined.

2.1 Overview

Earlier work outlined the likely benefits to U.S. industry as a result of Kigali ratification. The total industry is a significant contributor to the economy, employing 589,000 in the U.S. The benefits are driven by the HVACR equipment industry with a contribution from fluorocarbon manufacturing. Direct effects include an improvement of $12.4 billion in direct output in the U.S., 33,000 additional U.S. manufacturing jobs, $5.0 billion in value added, and $3.0 billion in labor income. Importantly, those benefits to U.S. industry come not from the pockets of U.S. consumers, but from a slowed rate of increase in equipment imports to the U.S. and an increased rate of exports of U.S.-manufactured equipment – improved market shares home and abroad rather than increased local prices.

The primary driver for the changed U.S. trade balance is the direction of the U.S. HVACR market. In the absence of Kigali ratification, there is little reason to expect strong near-term market demand for Kigali-compliant products in the U.S. In fact, significant regulatory uncertainty will drive industries to delay U.S. investment in new products and processes until there is more clarity about which products will be in demand. Most of the U.S. companies involved are multinational, and will also be attentive to global markets, the most important of which are sending clear market signals to manufacturers through their adoption of Kigali controls. The companies will certainly continue to invest in development and manufacture of Kigali-compliant products, but the facilities supplying the products will be strongly advantaged by being located near the sources of early, strong, and more certain demand. The U.S. companies may benefit regardless, but the additional U.S. jobs and improved trade balances are not likely without Kigali ratification.

If, however, Kigali requirements are implemented in the U.S., a large, fairly certain market will exist nearer the headquarters development facilities for most of those companies. Design and commercialization of new products can be simplified. Production in excess of local demand can and will be exported to other markets. Regulatory certainty and customers committed to the transition are expected to enable U.S. businesses to lead their efforts from their home bases and strengthen their participation in world markets, employing more workers in the U.S. to serve growing export markets and providing better products to the U.S. market, reducing imports of older technologies.

2.2 Alternatives to HFCs

Domestic implementation of the Montreal Protocol has worked to minimize consumer cost impacts by ensuring multiple options for technology transition and identification of reasonable timetables for transition. Industry has worked to achieve cost-effective transitions through coordination of design cycle changes with implementation of additional product development and manufacturing efficiencies. And opportunities for multiple options have driven healthy competition at all levels of the industry. Hence, the

Montreal Protocol has exhibited a track record of technology development and improved performance, which also achieves overall environmental objectives.

2.2.1 Product Supply and Pricing

In the case of the transition to be driven internationally by the Kigali Amendment, most of the replacement products are existing products. For example, HFC-32, hydrocarbons, and carbon dioxide are commercial products priced at relatively low levels. Some of the newer, but also already commercial, alternatives are blends incorporating these existing refrigerants with a quantity of one of several hydrofluoroolefins (HFOs). HFOs are also used alone in some applications. Additional options will continue to be developed, but the refrigerant and other supplier industries are prepared to supply the needed materials for the Kigali transition in the U.S. Some full-scale chemical manufacturing facilities are also in operation in the U.S., and the industry is prepared to expand to serve growth, both domestically and internationally.

Pricing of alternative products to meet Montreal Protocol requirements has been raised as an issue at each of the previous transitions. But in each case, the issue failed to emerge as a significant impact on consumer costs. An understanding of the normal product life cycle for new products explains why.

New product development is a costly endeavor and the development of refrigerants is no exception. In the early part of a product's lifecycle, it can cost as much as hundreds of dollars per pound to prepare a small quantity of a new product for laboratory testing. When larger quantities are produced, the costs are reduced. For example, production cost for such a product in a pilot plant might be less than one hundred dollars per pound and from a small commercial facility might be tens of dollars per pound. Manufacturing cost reductions continue throughout the product's growth period as facilities become larger and more efficient to realize economies of scale, investments are recovered, and the producers pursue optimizations like yield improvements and other process refinements.

The industry's experience with HFC-134a is instructive. When this refrigerant was first introduced to replace CFC-12 in automobiles, it was estimated that its long-term cost would be as much as ten times the material it was replacing. In fact, today's bulk prices are competitive in real dollars with refrigerants from the early 1990s. The early commercial pricing for HFC-134a was somewhat higher but was driven down very quickly by competition and manufacturing experience.

A few of the new generation refrigerants are still early enough in their life cycles that today's prices are well above their expected long-term levels. As before, there are unsupported predictions that long-term bulk prices will be as high as today's quoted retail prices for small quantities. Yet detailed analysis predicts otherwise. For instance, as worldwide demand for HFO-1234yf increases and global capacity is added to meet this demand, the cost of manufacture will continue to decline. Since HFO-1234yf was introduced, the auto industry has already seen its price decline significantly from growing economies of scale and increased competition. Long-term cost of HFO-1234yf is expected to equilibrate[7] at levels in line with the assumptions of the present study.

As countries around the world prepare to implement Kigali, lower costs will come about in concert with the effectiveness of the transition. In addition, there are only a few end

[7] Center for Climate and Energy Solutions (2017).

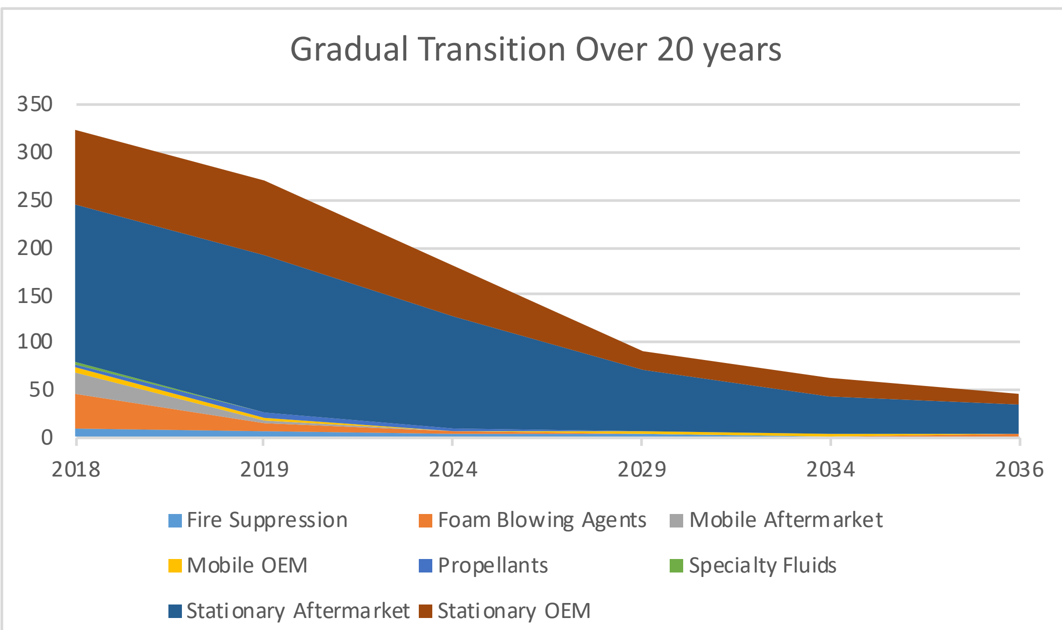
use applications where HFOs are used alone. If present in a low-GWP blend, the HFO component is at a relatively low percentage versus other lower cost refrigerants. Thus, even if HFO prices are high early in the life cycle, they will have minimal impact on the price of low-GWP refrigerant blends.

The average price of refrigerants over time will reflect the mix of materials being used at the time and their weighted costs. For the Kigali Amendment transition, prices will be a blend of remaining use of existing materials, transitions to lower cost refrigerants, and transitions to blends and other new refrigerants. Expected transitions over time have been studied for each use by industry, EPA, CARB, and others. The average refrigerant and other new materials market prices are not expected to change significantly in real dollars during Kigali implementation, if Kigali is ratified in a timely manner. The following section includes an explanation of how delays can require rapid, expensive changes instead of a smooth transition.

2.2.2 Changes in Demand Related to Kigali Ratification

Industry participants and regulators study the prospective adoption rates for various next generation materials and technologies, both to plan facilities to make materials and products available to support growth and to ensure that environmental goals can be met in a timely manner. In some cases, likely changes are studied for each application in the market. One such forecast for the U.S. market was translated into a total contribution to global warming, calculated as volume multiplied by global warming potential (GWP) for each material and grouped by industry segment for a total contribution from each segment, measured in millions of CO_2-equivalent metric tons.[8] The results shared with the authors contain no individual product forecasts, but only how the segments overall are expected to reduce their contributions to global warming.

Figure 2.1: GWP-Weighted Product Consumption by Industry Segment -- Gradual



[8] Private communication from an industry participant.

Figure 2.1 shows the GWP-weighted consumption of all existing and new products for each of the major segments in the case of gradual adoption of new products and technologies consistent with the scheduled Kigali requirements. This is how segments are likely to change with timely ratification of Kigali in the U.S.

Without ratification of Kigali, any changes in the U.S. are expected to be much slower to develop, if at all in some cases. The incentive to act is minimal, and the forecasted GWP-weighted product consumption is shown in Figure 2.2. There is essentially no reduction in GWP-weighted product consumption over the period, as any transitions taking place are offset by industry growth.

Figure 2.2: GWP-Weighted Product Consumption by Industry Segment – No Transition

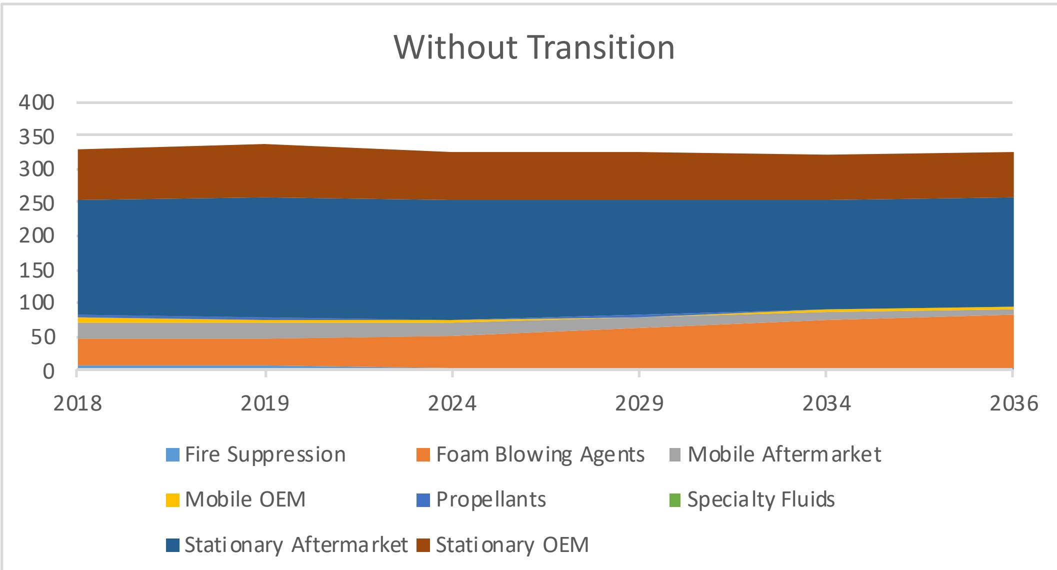
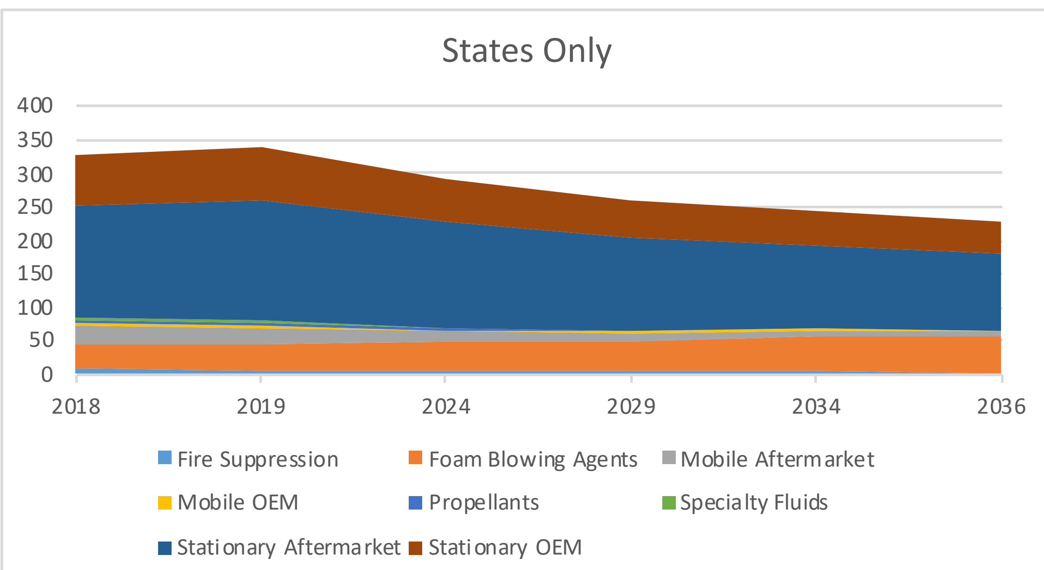


Figure 2.3: GWP-Weighted Product Consumption by Industry Segment – States Only

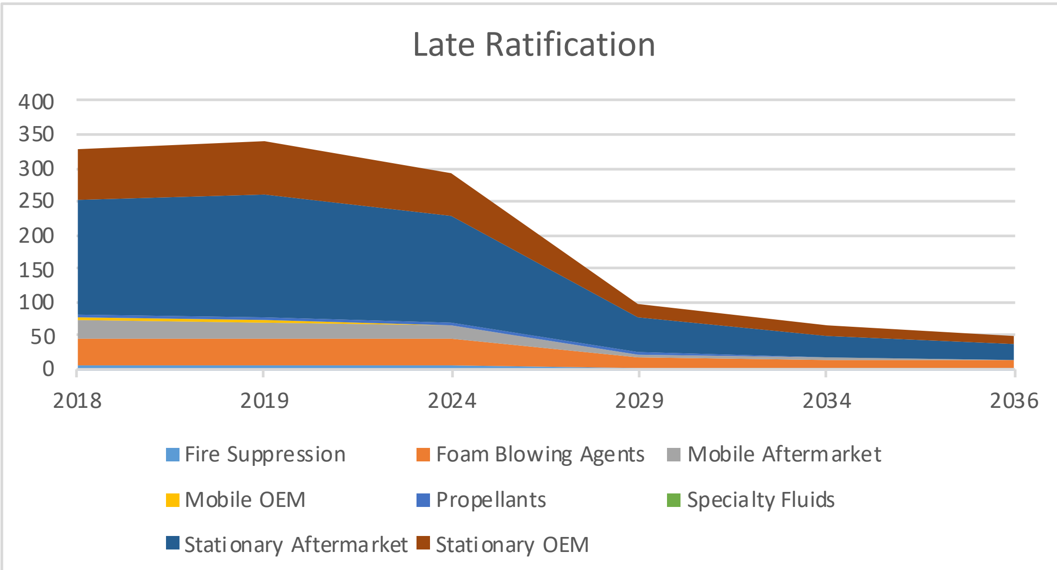


As discussed elsewhere in the report, in the absence of Kigali ratification, a number of individual states likely would choose to regulate. That possibility is shown in Figure 2.3.

There is less environmental benefit, and piecemeal actions could be expected to add to industry costs. It is unclear the extent to which these industry costs would be translated into consumer costs.

A final forecast considered the case where Kigali is ratified in the U.S., but only after a delay of five years. Little action is expected in the uncertain environment before the ratification, followed by a rapid, more expensive transition to meet the Kigali requirements in later years. This is shown in Figure 2.4. Previous experience has demonstrated the benefits of the methodical transition provided by the Montreal Protocol's gradual reduction schedules as compared with significant short-term curtailments is reflected in the figure.

Figure 2.4: GWP-Weighted Product Consumption by Industry Segment – Late Ratification



These forecasts are indicative of the kinds of changes that will take place as the Kigali Amendment goes into force globally in 2019, depending on the kind of action taken in the U.S. Timely U.S. ratification of the Kigali Amendment provides the smoothest, least costly transition, especially because it happens in concert with the rest of the developed countries.

2.3 Industry Actions

The costs that fall to consumers are obviously determined by a combination of what products are available on the market and what choices the customers make among those products. Industry, however, must make some of its choices in advance of actual consumer demand. Development cycles, other regulatory requirements, and facility construction or modifications all create time constraints. To understand impact on consumers, one needs a view of the future market choices.

2.3.1 Available Alternatives

In addition to the refrigerants that are dominant in today's market, a number of new choices have become available, including hydrofluoroolefins (HFOs) and hydrocarbons. Some, notably hydrocarbons, are less expensive even than today's refrigerants. But they bring flammability concerns, requiring additional equipment engineering to prevent leaks, to provide additional fireproofing, and so on. Some applications, like household refrigerators, require only small volumes of refrigerant, are largely leak-free already, and are moving to newer refrigerants.

Where larger refrigerant volumes are involved, some of the new refrigerants have very low flammability that requires less significant design changes. One of the concerns has been the high prices of such products when demand is still low, products are early in their life cycle, and production costs remain high. In this case, the history of previous transitions is relevant. During both of the previous Montreal Protocol transitions, away from CFCs and away from HCFCs, the HFCs that replaced them were initially expensive, but competition, manufacturing scale, and the typical learning curve for new products has brought prices back to more traditional levels.

Another important consideration is the energy efficiency of the cooling system. Refrigerants vary in their own contributions to efficiency, with some improving energy efficiency as much as 10%. System design can achieve additional efficiency in other ways as well, with possible tradeoffs in design and development cost. Ongoing requirements for efficiency improvements in overall systems create a pressure to find the most favorable options for achieving the required efficiencies.

Of course, manufacturers also consider expected long-term refrigerant pricing in making their selections, but next generation refrigerant prices are expected to decline, with increased market growth and competition, toward cost parity. Manufacturers also look to experience from previous transitions for guidance. When R134a, an HFC, was first introduced in the 1990s, there were predictions of long-term pricing between $4.50 and $12/lb. for bulk purchases ($7.70 to $20/lb. in current dollars). Recent distributor prices are in the neighborhood of $3/lb.[9], demonstrating the expected decline over time as volumes and competition have increased and manufacturing processes have been refined.

The history of pricing has been highly dependent on the gradual chemical phasedowns and logical user transitions under the Montreal Protocol. Experience with the European Union F-gas rules reaffirms the need for both. Europe has experienced extraordinary cost increases because they failed to coordinate the chemical phasedown with the equipment and other end-user transitions; they accelerate the Kigali phasedown ahead of the ability to achieve the transition; and they significantly impacted the existing equipment base by limiting availability of current HFC supply for this importance service need. This is precisely opposite what U.S. industry is urging for implementation in the U.S.

Equipment manufacturers' decisions on what equipment to design and produce take all of these factors into account. They also note that the volume of refrigerant constitutes a relatively small part of the cost of a new air conditioning unit. Further, with the ongoing effort to contain leaks, the need for replacement refrigerant during the equipment's operating lifetime is also reduced, minimizing the impact on service costs.

2.3.2 Equipment Design

Air conditioning manufacturers operate with a design cycle that ensures new equipment meeting all anticipated regulatory requirements will be available as needed for commercial introduction. Refrigerant suppliers work with them to ensure that the chosen

[9] Private communication from a supplier.

refrigerants will also be available. Early in the design cycle, the expected regulatory environment must be anticipated, to ensure that efficiency and other regulatory requirements will be met. Having the clarity of Kigali timelines will enable design cycles to be completed meeting both sets of requirements.

Design cycles are full of tradeoffs: a low-cost refrigerant might require more expensive components in some parts of cooling equipment. A more expensive refrigerant might offer equipment savings or energy efficiency elsewhere. Manufacturers seek to manage these tradeoffs while meeting all the external requirements, and the balance can be different in different segments and applications.

One of the biggest challenges during a period of transition is understanding what the requirements will be. The Montreal Protocol, and more recently the Kigali Amendment, acknowledged this challenge by imposing gradual changes to allow the transition to be smooth, minimizing impacts on both manufacturers and consumers. By having date-certain and well-defined requirements, industry has clear design targets and can maintain an efficient design cycle.

Similarly, energy efficiency requirements are mandated to change over time, with the timing well understood. U.S. Department of Energy (DOE) efficiency rulemakings are anticipated in both 2023 and 2029. DOE cites advantages to manufacturers overall as a result of the standards and the way they are designed.[10] The periodic increases in DOE energy conservation standards are, however, a significant cost burden for manufacturers and these costs are ultimately passed on to consumers. Efficiency improvements generally require a larger heat transfer surface, meaning additional materials such as steel, aluminum and copper. To lessen the cost impacts of these efficiency increases, industry innovates to commercialize improved compressor technology and heat transfer surfaces, sources commodities and components from lower cost suppliers and incorporates new technologies to drive manufacturing efficiencies. Additionally, some alternate refrigerants are more efficient, allowing manufacturers to add less material content, again reducing the impact of these transitions.

Coordinating a refrigerant transition with energy conservation standards will significantly reduce the anticipated cost impacts associated with major design cycles, enabling industry to move quickly and efficiently to new equipment designs appropriate to the market. Without Kigali, separate uncoordinated design cycles will have a negative impact on consumer cost. The phasedown steps negotiated in Kigali create an opportunity to align the 2029 transition in residential and commercial split air conditioning systems while meeting the 2029 DOE-mandated efficiency improvement. The timing also allows for equipment safety standards and building codes to be updated and adopted by jurisdictions. For modeling purposes, meeting the DOE requirements is equivalent to about 1.5% per year improvement.

Regulatory uncertainty is a constant challenge. Some designs must be developed in case they are needed but may never be used if the regulatory environment does not develop as anticipated. Without federal action, some states or localities in the U.S. are implementing regulations on their own, as happened in the Montreal Protocol transition away from CFCs. Manufacturers are faced with the decision of single designs sufficient to meet all such requirements or multiple designs tailored to each regulatory environment. OEM sources[11] note that the costs of design cycles for the redesign of a product line (by

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[10] See Department of Energy (2017).
[11] Private communication from a U.S OEM.

major manufacturers) traditionally run in the $20-$50 million range depending on the time required and the complexity of the transition.

The cost of major product line transitions can be significantly reduced when both energy conservation standards and refrigerant transitions are combined and guided by certainty and predictability, allowing manufacturers to find efficiencies and synergies when executing their multi-generation product plans. Lack of coordination adds to design costs and ultimately to consumer costs. Multiple low volume lines also provide only very limited economies of scale, and the equipment from the lower volume lines will be more expensive. Alternatively, if regulations are non-uniform, an attempt to meet multiple conflicting requirements in a single design leads to higher cost of manufacture and can be made obsolete in a state with the passage of newer regulations, possibly impacting consumer prices.

As part of their design work, manufacturers are constantly working on developments to reduce their own costs in other ways to increase profits without increasing prices, or to counterbalance expensive improvements with savings elsewhere.

A final ongoing design effort across the industry seeks to reduce leak rates. For all equipment, this can reduce ongoing cost of ownership in addition to the environmental benefits. For refrigerants with any flammability risk, even low flammability, it's essential. Reduced leaking saves refrigerant costs and maintains sufficient charge to keep the equipment's performance near its optimum for longer. According to the EPA EnergyStar program, properly charged equipment operates 5%-20% more efficiently than improperly charged equipment.[12]

2.3.3 World Trade and Manufacturing Site Decisions

An important consideration for equipment manufacturers, most of which have multi-national operations, is the location of new manufacturing facilities. The markets for their products are international and their competition is global. Typically, companies will make choices that allow most of their production to flow to local markets, with an intent to export additional production. This can be especially important with new product introductions, where the earliest production facilities are often located where the market for the product is expected to be fastest growing.

For prior transitions under the Montreal Protocol, the U.S. was a consistent leader in implementing the required changes. Most U.S. companies designed and introduced new products in their home markets and used that base, as well as additional offshore facilities over time, to build their strength in world markets. Today, with much of the world having already committed to Kigali and the U.S.'s commitment far from certain, there is a great deal of pressure on U.S. companies to locate new facilities offshore, where their markets will be more certain. That decision would make the new delivered equipment prices higher in the U.S. after adding the cost of shipping back to the U.S. Similarly, the U.S. home market is constantly being challenged by imports of older equipment as the global market for equipment using current refrigerants shrinks with the implementation of Kigali. The large U.S. market offers the best prospect for sales of the outdated equipment. Conversely, with Kigali ratification, the U.S. would offer the most attractive market for sales of next generation technology and equipment.

[12] See Environmental Protection Agency (2009).

2.3.4 Anticipated Industry Responses

U.S. industry has necessarily begun its planning for product developments over the next several years. Some new equipment is being developed with new refrigerant choices, work is underway to meet energy efficiency requirements, and site selection decisions are already being considered for equipment using new refrigerants.

Without U.S. Kigali ratification, production will likely continue for equipment using HFC refrigerants, modified as necessary to meet energy efficiency requirements. More of it will likely be supplied by imports from other countries. New offerings will be available, but at a higher price because of smaller volumes and market prices influenced by the demand for such products in countries meeting Kigali's requirements. Similarly, alternative refrigerants will likely retain at least some of their low-volume higher pricing for the foreseeable future. Investments by U.S. companies in manufacturing facilities for new equipment using new refrigerants are more likely to be located offshore or, if required for meeting state regulations, to be smaller in scale.

In the event the Kigali Amendment is ratified, the incentive for U.S. domestic manufacturing becomes much greater. Both new refrigerants and the equipment to use them will be fully available to U.S. consumers at the most competitive prices in the world, and the volumes will grow sufficiently to quickly moderate the early, developmental scale pricing.

2.4 Market Implications

From the consumer's viewpoint, the decisions involved in compliance with Kigali are much simpler. Current air conditioning equipment owners want to maintain their existing equipment, with refrigerant recharging as necessary, throughout its useful life. The want to buy a new system only when their own needs dictate, independent of Kigali timing. A decision to purchase new or replacement air conditioning equipment is made from within the market offering at the time of purchase. A decision on new equipment in a given year is best looked at by considering the average market expected during that year. One can then consider the ownership experience throughout the equipment's useful life.

2.4.1 Support of Existing Equipment

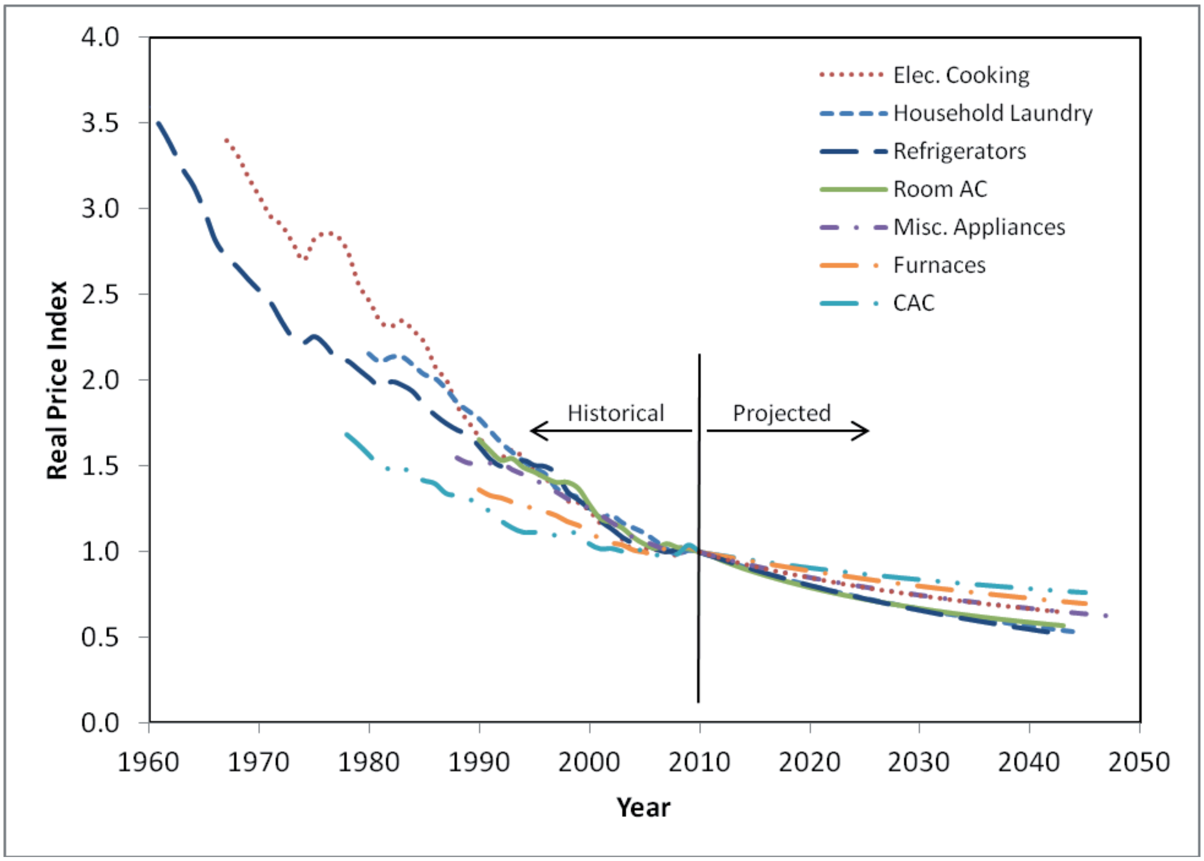
Owners of existing equipment will experience little or no impact from Kigali. Under the Montreal Protocol, regulated refrigerants remained available throughout the lifetimes of the equipment using them, and are still available today, long after production of the refrigerant was stopped. Some operating commercial equipment is more than thirty years old. The reclaim market has served as a buffer to provide products at reasonable prices, to meet the market demand. A similar situation will exist for HFCs post-Kigali, regardless of whether the U.S. participates. What that means is that there is no Kigali-driven mandate for an early purchase of new equipment, other than a consumer's own choice.

2.4.2 New Equipment Cost

When a consumer decides to purchase new air conditioning equipment, the choice will be made from equipment on offer at the time. Some purchasers will favor lower initial purchase costs; others will look for new features. Some, particularly commercial purchasers, will be guided by ongoing operating costs or expected total cost of ownership. Starting with what is on offer, they will shape the market by purchasing more of what they want and less of what they don't want. Historically, manufacturers consider an average of the prices paid for a given capacity air conditioning unit as one useful market measure. From the consumer's viewpoint, this is a one-time decision: What will I pay now for a unit to cool my house or building?

Markets, not just costs, drive pricing in competitive industries. Suppliers will try to pass along their cost increases, but that works only so long as customers continue to buy. Recent residential air conditioning equipment pricing has somewhat stabilized in constant dollars.[13] Historic data suggests that, despite the numerous transitions under the Montreal Protocol and domestic energy efficiency programs, real dollar pricing in central air conditioning (CAC), as well as room (window) air conditioning and refrigerators, declined between 1980 and 2010, as shown in Figure 2.5.[14]

Figure 2.5: Historical and Projected Real Price Indices for U.S. Major Appliance Categories



It is reasonable to assume that consumers will continue to face an array of different choices meeting whatever regulatory requirements are in place at the time, but without a significant change in average market pricing.[15] It is possible that a slight increase in the average might occur with Kigali, but that is not the historical experience.

[13] Goetzler, et al. (2016).
[14] See Desroches, et al. (2018). Historical trends based on the PPI published by the U.S. Bureau of Labor Statistics. Projected trends are experience curve fits to the historical data.
[15] See Navigant (2018)

2.4.3 Operating Expenses

A final important consideration for consumers can be their ongoing operating costs for a piece of air conditioning equipment. The primary contributors are operating costs, in the form of electricity, and maintenance, including the cost of refrigerant for recharging as needed.

The size of a unit and of course its energy efficiency determine its electricity requirement. For a given size, then, it is reasonable to look at the average energy efficiency expected to be offered by the manufacturers. This is driven largely by regulatory requirements. Over the long term, those efficiencies will increase. Equipment bought in the future will consume less electricity over its lifetime than equipment bought today. However, the inherent efficiency advantages of the low-GWP alternatives for residential and light commercial applications that would transition in 2029 offer an advantage of improved cycle efficiency. In line with modeling by CARB, this benefit has been valued in the present study as an efficiency increase of about 1.3% in the compliant products using low-GWP refrigerants in 2029 with Kigali ratification. relative to products sold in 2029 without Kigali.[16] An alternative would be to reflect the benefit as reduced cost of commodity metals required to achieve the mandated efficiency. In fact, this is considered the more likely scenario for all but the most efficient equipment lines. The benefit from reduced initial consumer cost would be comparable to the alternative efficiency benefit.

Average costs for a maintenance or service visit will not differ markedly for consumers facing 'with Kigali' or 'without Kigali' market scenarios. However, the increasing effort necessary to reduce leak rates with new refrigerants because of even minor flammability concerns is expected to have a significant impact on the market. Leaks tend to happen when a system is compromised for some reason rather than slow leaks over time. Current equipment can be considered to have about a 10% per year leak rate on average, meaning one to two full refrigerant recharges over a fifteen-year lifetime.[17] Kigali-compliant equipment is expected to reduce that to 5% per year, or roughly one full replacement over a lifetime.

The impact of Kigali on maintenance costs, then, consists of a reduction in replacement refrigerant volume and a reduction in the average cost of maintenance and service due to fewer visits. For the attentive consumer, these costs will factor into their purchase decisions, but again, their choices will be limited by the products available at the time. A non-Kigali scenario is not likely to offer the lifetime savings.

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[16] California Air Resources Board (2017).

[17] Both the current estimated leak rate and the improvements associated with Kigali compliance for flammable and low-flammability refrigerants are estimates from industry sources familiar with design targets.

3 Consumer Impacts of Kigali Ratification

Consumer impacts under Kigali benefit from the phased-in controls. Existing refrigerants remain available for servicing existing equipment. New equipment purchases are not accelerated other than by customer choice. The same is true in most applications.

The cost issue for consumers is therefore focused on their new equipment purchases and what they will experience. We have selected two of the largest applications in the HVACR industry and largest users of HFCs for a detailed analysis of the cost of ownership over the lifetime of the equipment. These applications are residential and commercial air conditioning. The former is well-represented by an average sized unit of 2.5 tons capacity. The latter, typically rooftop units on commercial buildings, is well represented by a nominal 15-ton unit. We began by assessing the costs of a purchase in 2019, using it as the basis for projections for costs with and without Kigali implementation in 2029.

We also conducted a brief assessment of several other HFC-using applications considering the impacts of Kigali. Many share characteristics with the air conditioning applications, however these assessments are primarily qualitative.

3.1 Methodology: Calculation of Life Cycle Cost

Life cycle cost analysis[18] can be used to compare the average cost of ownership and use for alternative equipment with similar operating characteristics. For this analysis, we have collected from several of the individual producers of air-conditioning equipment, or projected based on their input, information[19] on the following operating characteristics:

1. Initial cost of the equipment, including the initial charge of refrigerants.
2. Average service life.
3. Resale value at the end of life, if any, or disposal cost.
4. Annual fuel and/or electricity expense.
5. Average annual service cost, including parts and refrigerant replacement.

For each type of equipment considered, we first evaluate current (2019) cost parameters. We then project likely future (2029) cost for the two cases – with and without Kigali ratification. All projections are based on the data collection and interviews. Conservative assumptions made for each air conditioning application are described.

To estimate the life-cycle cost (LCC) from these parameters, we will use the following formula:

$$LCC = I - Res + E + OM\&R + O$$

LCC = Total LCC in present-value (PV) dollars of each given alternative

I = Initial investment cost

Res = PV residual value (resale value, salvage value) less disposal costs

[18] See Fuller and Petersen (1995) for a standard government reference on life-cycle costing.
[19] California Air Resources Board (2017).

E = PV of energy costs

OM&R = PV of non-fuel operating, maintenance and repair costs, including refrigerant replacement

O = PV of other costs

When calculating present value, we have considered both the undiscounted sum of costs and the costs discounted at 7 percent, over the average expected lifetime of the equipment.

3.2 Residential Air Conditioning

3.2.1 Current Cost Variables

Figure 3.1 presents important variables to be considered in calculating the full life-cycle cost of a nominal residential AC (2.5-ton) unit. Average refrigerant cost, average charge size, installed cost, annual service and maintenance cost and average electricity consumption are based on the collective input of the industry, plus analysis by CARB in the case of refrigerant cost and electricity consumption. Average electricity cost uses the DOE/EIA Projected Electricity Prices from the Annual Energy Outlook 2018, expressed in 2019 dollars. Annual refrigerant cost is calculated as the replacement cost for an average leak or loss rate of 10% of the charge size per year, although the replacement would likely not occur in those increments.

Figure 3.1: Life Cycle Cost Variables for a 2.5-Ton Residential Unit, 2019

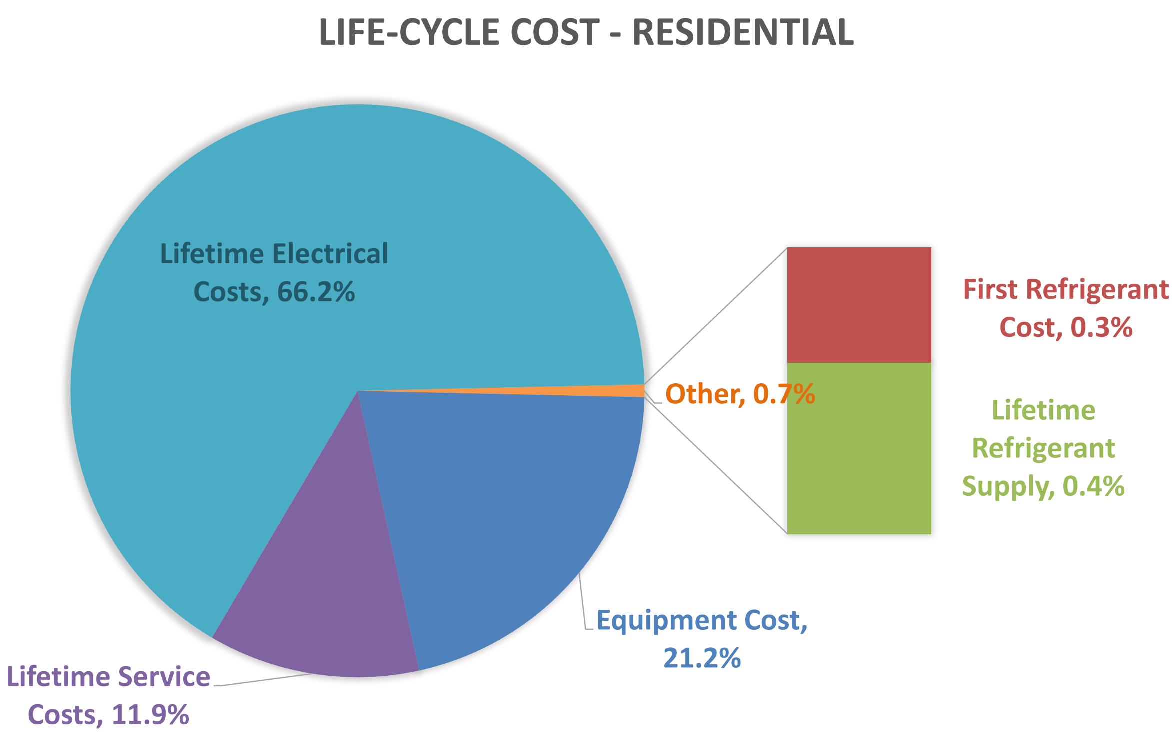
Installed Cost	Initial Refrigerant Cost	Expected Life (Years)	Annual Operations Cost	Annual Electricity Cost	Electricity Consumption	Avg Electricity Cost ($/Kwh)	Annual Refrigerant Cost	Average Charge Size (lbs/unit)	Regrigerant Cost ($/lb)	Annual Service & Maintenance Cost
$4,000	$53	15	$838	$832.39	6,125	$0.136	$5.250	7.5	$7.00	$150

We start with the initial cost and initial refrigerant cost. For the life of the equipment (15 years), we cumulate the annual operations cost and annual service and maintenance cost. Operations cost is further divided into annual electricity cost and annual refrigerant cost. All dollar figures are in 2019 constant prices. In this modeling, we assume, for simplicity that the parameters don't change over the lifetime of the equipment.

Undiscounted total initial and annual cost using the formula in section 3.1 comes to $18,867.06. Average annual cost is $1,257.80. The calculation can also be done with discounting, at a 7 percent rate. Discounting puts more weight on the initial installation cost, and less weight on cost savings that may occur in future years. The total discounted cost is $12,637.35. Average discounted cost per year is $842.49.

Figure 3.2 shows the breakdown in costs for the life cycle of a residential air conditioner. The dominant component in total costs for purchase of a home air conditioner, even in the discounted case is energy consumption at over 66%, followed by initial investment at 21% and annual service and maintenance at 12%. The contribution of initial refrigerant and replacement charges to cost is approximately 0.7% of the total.

Figure 3.2: Life Cycle Cost Breakdown for a 2.5-Ton Residential Unit, 2019



3.2.2 Projected Cost Variables: 2029

Surveys of industry experts and CARB projections formed the basis for the following conservative assumptions about how costs will change between now and 2029. All costs are expressed in 2019 dollars.

- In the absence of Kigali, we expect no difference in the cost of an average unit. For the Kigali case, we assume conservatively that low-GWP equipment in 2029 would be roughly 10 percent more expensive. We were cautioned that historical prices in constant dollars have come down over time, that most of the changes required would likely be offset by other manufacturing cost reductions, and that ongoing design cycle costs are already priced into equipment. For the analysis, we chose conservatively to allow for potential increase.
- By 2029 low-GWP refrigerant blends and high-GWP refrigerant blends would have approached the same cost ($7/lb.). This assumption is based on extensive CARB analysis of likely shifts in refrigerant choice combined with analysis of pricing patterns over time for previous generations of refrigerants. We will explore the sensitivity to this assumption as part of the analysis.
- Efficiency opportunities with the low-GWP equipment can be used by manufacturers to minimize cost while achieving energy targets. However, in line with previous modeling, the benefit will be modeled as an increase in energy efficiency of 1.3 percent relative to high-GWP equipment.
- The average refrigerant charge size in the low-GWP equipment is approximately 6.7% smaller than for today's equipment, based on trends noted by manufacturers from their own design work.

- The low-GWP residential and commercial air conditioning equipment is assumed in the model to have a significantly lower leak rate, 5 percent instead of 10 percent per year average. Industry constantly works to minimize leaks, and some types of equipment are already even tighter than this. However, the acceptance of flammability in refrigerants will accelerate this effort, justifying the assumed improvement.

3.2.3 Life Cycle Costs: 2029

Using the projections from engineers and economists from 6 of the top U.S. producers of air-conditioning equipment, we calculated the lifetime costs of ownership and use. Figure 3.3 shows the results of projecting life-cycle costs, both with Kigali ratification and without. Again, all values are in 2019 dollars.

Figure 3.3: Life Cycle Cost Variables for a 2.5-Ton Residential Unit, 2029 Projections

	Installed Cost	Initial Refrigerant Cost	Expected Life (Years)	Annual Operations Cost	Annual Electricity Cost	Electricity Consumption	Avg Residential Electricity Cost (2019$/Kwh)	Annual Refrigerant Cost	Average Charge Size (lbs/unit)	Regrigerant Cost (2019$/lb)	Annual Service & Maintenance Cost
Without Kigali	$4,000	$53	15	$778	$772.32	5,272	$0.1465	$5.25	7.5	$7.00	$150
With Kigali	$4,400	$49	15	$765	$762.24	5,203	$0.1465	$2.45	7.0	$7.00	$130

The results of these assumptions using a static calculation (no discounting) is shown in Figure 3.4. The results with discounting are in Figure 3.5. Note that in either case, the life cycle costs are not much different. Both comparisons represent a tradeoff between higher initial cost with the low-GWP equipment and refrigerants and lower annual operations and maintenance costs. With the simple static computation, the low-GWP equipment life cycle cost with Kigali is slightly lower. In the discounted case shown in Figure 3.5, the cost savings in the future are given less weight and are not quite sufficient to offset the higher initial cost.

Figure 3.4: Comparison Using Static Calculation (undiscounted) for 2029

	Total	Annual Average
Without Kigali	**$17,966**	$1,197.74
With Kigali	**$17,869**	$1,191.29

Figure 3.5: Comparison Using Discounting for 2029

	Total	Annual Average
Without Kigali	**$12,165**	$810.97
With Kigali	**$12,273**	$818.23

One cost element in particular has been the subject of much speculation. Although our analysis and the input that was collected both support our refrigerant price assumptions, we have explored the sensitivity of the results to a much higher price. The same calculation was performed with a refrigerant cost of $35/lb. instead of $7, a factor of five difference. For the high refrigerant cost, the total cost in the undiscounted calculation increases by $343 from $17,869 to $18,212, or an annual average of $1,214.15, an increase of 1.9%, and only 1.4% per year more than the 'without Kigali' cost. The discounted total for the 'with Kigali' case increases $282 from $12,273 to $12,555, or an annual average of $837.01, an increase of 2.3%.

The consumer cost impacts over a full life cycle in the 'with Kigali' scenario in comparison to the market expected without Kigali range from a small benefit in an undiscounted calculation to a small added cost in a discounted calculation, less than one percent in both cases. Even if refrigerant prices have been underestimated by a factor of 5, life cycle costs do not markedly increase. To the extent the initial equipment pricing, as very reasonably predicted by some respondents, avoids the 10% increase used here, that would reduce the 'with Kigali' costs by $400 in both the undiscounted and discounted cases, more than offsetting any increase in the refrigerant price.

3.3 Commercial Air Conditioning

3.3.1 Current Cost Variables

Figure 3.6 presents important variables to be considered in calculating the full life-cycle cost of a nominal commercial AC (15-ton) unit. Average refrigerant cost, average charge size, installed cost, annual service and maintenance cost and average electricity consumption are based on the collective input of the industry, plus analysis by CARB in the case of refrigerant cost and electricity consumption. Average electricity cost uses the DOE/EIA Projected Electricity Prices from the Annual Energy Outlook 2018, expressed in 2019 dollars. Annual refrigerant cost is calculated as the replacement cost for an average leak or loss rate of 10% of the charge size per year, although the replacement would likely not occur in those increments.

Figure 3.6: Life Cycle Cost Variables for a 15-Ton Commercial Unit, 2019

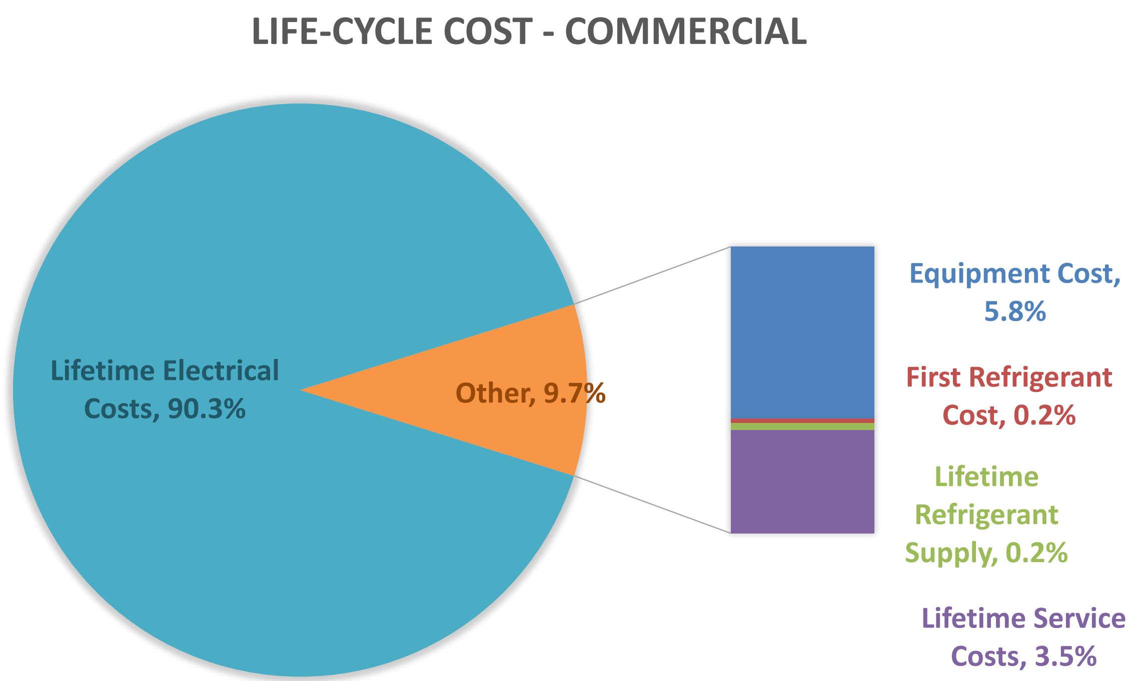
Installed Cost	Initial Refrigerant Cost	Expected Life (Years)	Annual Operations Cost	Annual Electricity Cost	Electricity Consumption	Avg Electricity Cost ($/Kwh)	Annual Refrigerant Cost	Average Charge Size (lbs/unit)	Regrigerant Cost ($/lb)	Annual Service & Maintenance Cost
$25,000	$700	15	$26,060	$25,990.00	230,000	$0.113	$70.00	100.0	$7.00	$1,000

We start with the initial cost and initial refrigerant cost. For the life of the equipment (15 years), we cumulate the annual operations cost and annual service and maintenance cost. Operations cost is further divided into annual electricity cost and annual refrigerant cost. All dollar figures are in 2019 constant prices. In this modeling, we assume, for simplicity that the parameters don't change over the lifetime of the equipment.

Undiscounted total initial and annual cost using the formula in section 3.1 comes to $430,600.00. Average annual cost is $ $28,773.33. The calculation can also be done with discounting, at a 7 percent rate. Discounting puts more weight on the initial installation cost, and less weight on cost savings that may occur in future years. The total discounted cost is $ $261,652.36. Average discounted cost per year is $17,443.49.

Figure 3.7 shows the breakdown in costs for the life cycle of a residential air conditioner. The dominant component in total lifetime costs for purchase of a commercial air conditioner, even in the discounted case, is energy consumption at over 90%. Even the annual energy cost is greater than the initial equipment investment, which is less than 6% of lifetime costs. After those two elements follows annual service and maintenance at less than 4%. The contribution of initial refrigerant and replacement charges to cost is approximately 0.4% of the total.

Figure 3.7: Life Cycle Cost Breakdown for a 15-Ton Commercial Unit, 2019



3.3.2 Projected Cost Variables: 2029

Surveys of industry experts and CARB projections formed the basis for the following assumptions about how costs will change between now and 2029. All costs are expressed in 2019 dollars.

- In the absence of Kigali, we expect no difference in the cost of an average unit. For the Kigali case, we assume conservatively that low-GWP equipment in 2029 would be roughly 10 percent more expensive. We were cautioned that historical prices in constant dollars have come down over time, that most of the changes required would likely be offset by other manufacturing cost reductions, and that ongoing design cycle costs are already priced into equipment. We chose for the analysis to allow for possible increases.
- By 2029 low-GWP refrigerants and high-GWP refrigerants would have approached the same cost ($7/lb.). This assumption is based on extensive CARB analysis of likely shifts in refrigerant choice combined with analysis of pricing patterns over time for previous generations of refrigerants. We will explore the sensitivity to this assumption as part of the analysis.

- Additional engineering improvements in the low-GWP equipment achieve an increase in electricity efficiency of 1.3 percent relative to high-GWP equipment. However, both types of equipment are more efficient than the 2019 vintage.
- The average refrigerant charge size in the low-GWP equipment is approximately 6.7% smaller than for today's equipment, based on trends noted by manufacturers from their own design work.
- The low-GWP equipment has a significantly lower leak rate, 5 percent instead of 10 percent per year average. This is consistent with design intent to minimize leaks over time in this equipment.

3.3.3 Life Cycle Costs: 2029

Using the projections from engineers and economists from 6 of the top U.S. producers of air-conditioning equipment, we calculated the lifetime costs of ownership and use. Figure 3.8 shows the results of projecting life-cycle costs, both with Kigali ratification and without. Again, all values are in 2019 dollars.

Figure 3.8: Life Cycle Cost Variables for a 15-Ton Commercial Unit, 2029 Projections

	Installed Cost	Initial Refrigerant Cost	Expected Life (Years)	Annual Operations Cost	Annual Electricity Cost	Electricity Consumption	Avg Commercial Electricity Cost (2019$/Kwh)	Annual Refrigerant Cost	Average Charge Size (lbs/unit)	Regrigerant Cost (2019$/lb)	Annual Service & Maintenance Cost
Without Kigali	$25,000	$700	15	$23,489	$23,419.00	197,963	$0.1183	$70.00	100.0	$7.00	$1,000
With Kigali	$27,500	$653	15	$23,146	$23,113.12	195,377	$0.1183	$32.67	93.3	$7.00	$867

The results of these assumptions using a static calculation (no discounting) is shown in Figure 3.9. The results with discounting are in Figure 3.10. Note that in either case, the life cycle costs are not much different. Both comparisons represent a tradeoff of higher initial cost with the low-GWP equipment and refrigerants with lower annual operations and maintenance cost. The discounting places a lower weight on the cost savings in the future, when making the comparison. With both the simple static computation and the discounted calculation, the low-GWP equipment in the 'with Kigali' case has slightly lower total cost of ownership.

Figure 3.9: Comparison Using Static Calculation (undiscounted) for 2029

	Total	Annual Average
Without Kigali	$393,035	$26,202.34
With Kigali	$388,340	$25,889.34

Figure 3.10: Comparison Using Discounting for 2029

	Total	Annual Average
Without Kigali	$239,868	$15,991.19
With Kigali	$238,153	$15,876.90

One cost element in particular has been the subject of much speculation. Although our analysis and the input provided support our refrigerant price assumptions, we have explored the sensitivity of the results to a much higher price. The same calculation was performed with a refrigerant cost of $35/lb. instead of $7, a factor of five difference. For the high refrigerant cost, the total cost in the undiscounted calculation increases by $4,574 from $388,340 to $392.914, or an annual average of $26,194.23, still 0.03% less than the 'without Kigali' cost. The discounted total for the 'with Kigali' case increases by $3757 from $238,153 to $241,910, or an annual average of $16,127.30, less than 0.9% higher than the 'without Kigali' cost.

The consumer cost impacts over a full life cycle in the 'with Kigali' scenario in comparison to the market expected without Kigali show lower total cost with Kigali, whether discounted or not. Even if refrigerant prices have been underestimated by a factor of 5, the undiscounted life cycle cost remains lower with Kigali. But the discounted total shows a small increase with less weight given to future benefits. To the extent the initial equipment pricing, as very reasonably predicted by some respondents, avoids the 10% increase assumed here, that would reduce the 'with Kigali' costs by $2500 in both the undiscounted and discounted cases, more than offsetting any increase in the assumed refrigerant price.

3.4 Other Consumer Markets

In addition to the detailed consumer cost estimates for the two large air conditioning sectors, we have gathered information regarding the potential impact on other segments. In many cases, parallels can be drawn to the air conditioning application. In others, manufacturers are moving to non-fluorocarbon refrigerants. These are addressed next.

3.4.1 Other Commercial Air Conditioning and Refrigeration

Most refrigeration applications share some similarities with the residential and commercial air conditioning segments. Efficiency targets and refrigerant transitions present similar challenges, although the technology solutions may differ.

Manufacturers of large commercial chillers[20] have already commercialized equipment using next generation refrigerants. In fact, some large capacity chillers that use low-pressure, low-GWP refrigerants have increased efficiency over the HCFC and HFC refrigerants they replace. Some customers are purchasing this equipment purely for the decreased energy costs over its life cycle. With certainty as to the regulatory future, other consumers will choose to convert existing equipment if that investment will pay back in future energy savings. The primary impact of Kigali ratification for this industry will be certainty, enabling them to focus their product lines on the new refrigerants. Energy cost savings can offer a very large incentive to invest in new technology in this segment because of its dominant contribution to total costs of ownership.

3.4.2 Automotive Air Conditioning

Like the stationary air conditioning systems discussed in detail above, the automotive air conditioning industry continues to drive for lower refrigerant charges, greater efficiency, and reduced average leak rates. Approximately 60% of the industry has already

[20] GIZ (2015).

transitioned to low-GWP HFO refrigerants.[21] Because these are small systems, the added cost for a manufacturer to convert to a new refrigerant, including both refrigerant costs and equipment differences is estimated by industry experts to be less than 0.1% of the vehicle price.

In terms of lifetime costs, servicing of automotive systems must be considered. Again, over the long term, refrigerant costs are expected to be similar, with or without Kigali, and are mitigated in any case by the reduced charge. Historically, the transition to R134a was predicted in 1994 to lead to recharging costs in 1996 and beyond of as much as $200 ($318 in current dollars).[22] Yet recent quoted repair shop charges range between $123 and $156[23], less than half the predictions. There is little reason to expect the current transition to be different as new refrigerants gain economies of scale and increased competition.

3.4.3 Home Refrigerators

In 2016, the Association of Home Appliance Manufacturers (AHAM) announced that members will voluntarily transition to new generation refrigerants by 2024[24]. The transition is underway. Prior to the change, the R134a refrigerant in a single refrigerator would cost $1.00 to $1.50.[25] Most units are moving to isobutane, at a cost of $0.05 per refrigerator.[26] The reduced cost helps offset the capital required to retool for the new flammable or mildly flammable refrigerant, including fireproofing manufacturing facilities and making a system with extremely low leak rates even tighter.

The same replacement process is also underway for the insulating foams in the walls of refrigerators. A number of alternative blowing agents are already available with manufacturers making different choices based on their design needs.

Underlying these changes is the long-term pricing trend. Figure 3.11, from the Appliance Standard Awareness Project, shows the long-term trends in price, energy consumption and effective volume for refrigerators in the U.S. market. Since the early 1970s, even as they have gotten larger, these appliances have dramatically cut their energy consumption and their prices have declined by half. And in an earlier report they note,[27] "Between 1987 and 2010, real prices [of refrigerators] decreased by about 35% while average energy use decreased by more than 50%." The time period begins before the Montreal Protocol went into effect and includes the Protocol's previous transitions. Consumers have seen not more cost but rather benefits. With the industry's aggressive movement to next generation refrigerants, that trend should continue.

The primary importance of U.S. Kigali compliance in the home refrigerator sector is the clarity it provides on timing, allowing a coordinated design cycle, including refrigerant changes and new foams along with energy efficiency requirements. AHAM has estimated that inability to coordinate design cycle requirements could lead to tens of

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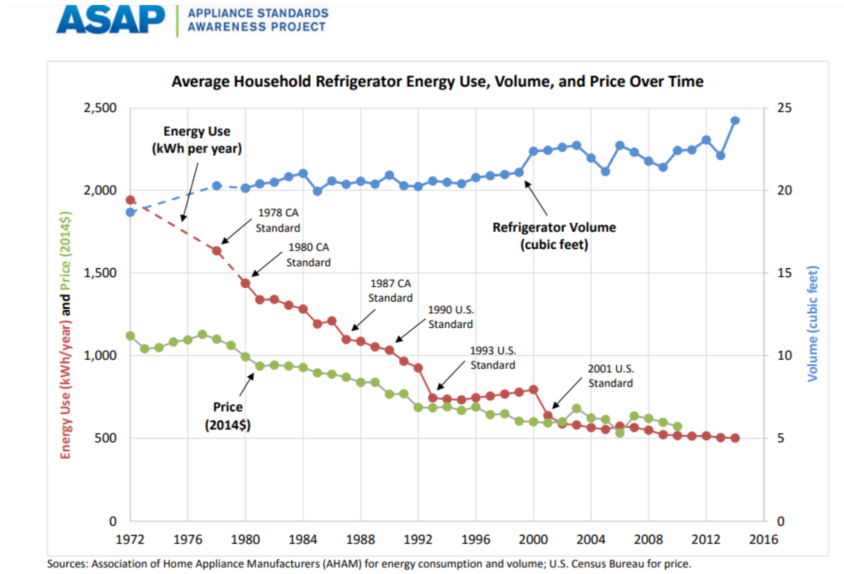
[21] Chemours (2018).
[22] Lieberman (1994).
[23] Johnson (2017).
[24] Association of Home Appliance Manufacturers (AHAM) (2016).
[25] Assumes 0.3 lb. of refrigerant (ICF International Report on the Assessment of Refrigerator/Freezer Foam End-of-Life Management Options) and bulk pricing of HFC 134a.
[26] Assumes cost of isobutane is $0.29 per pound and reduced charge size (communications with manufacturers).
[27] Appliance Standards Awareness Project (n.d.).

million dollars of added design costs for the industry and additional consumer expense, as would a patchwork of regulations at the state level.

Figure 3.11: Refrigerator Energy Use, Volume, and Price History[28]



3.4.4 Window Air Conditioning Units

Like refrigerators and other household appliances, the cost of a window air conditioner has continually declined over time in real dollars. According to Mark Perry[29], the price of an 8000 BTU room air conditioner in 1973 was $216.75. In 2015, Kenmore's 8000 BTU unit was priced at $219.99. This is essentially flat in current dollars, but at average U.S. wages in 1973, it took over 50 hours of work to purchase a unit. In 2015, it took only 10.4 hours of average wages for the same purpose, and the unit consumed significantly less energy. This continuing trend includes all previous refrigerant transitions. The quantity of refrigerant in these units is small and it is rarely replaced, so the service contribution is minimal.

3.4.5 Foam Insulation

The experience with prior transitions away from CFCs and HCFCs led producers in several foam applications to explore the use of alternative blowing agents in addition to using HFCs. Today, for many foam types, OEMs and consumers can choose from several solutions that are commercialized in the U.S. and globally.

In general, foam insulation provides savings to consumers that far outweigh the cost of the materials. Prices vary among the different foam choices, but the total cost of the foam remains a very small fraction of cost of buildings, refrigerators, or most of foam's other applications. On a lifetime cost basis, considering energy savings, even the more expensive options can deliver savings supporting additional initial investment, although competition can drive builders to less efficient solutions. The consumer can benefit from lower initial cost or benefit even more from higher energy efficiency.

[28] Appliance Standards Awareness Project (2016).
[29] Perry (2018).

3.4.6 Refrigeration and Air Conditioning Equipment Service

Equipment service was considered in the life cycle cost calculations for residential and commercial air conditioning. Predicted high costs for auto air conditioning service, as discussed above, never materialized. Similarly, service costs have remained and are predicted to remain reasonably stable in other sectors as well.[30] Reduced leak rate and charge size have contributed.[31] With Kigali, additional leak reduction and smaller charge sized using next generation refrigerants lowers the frequency of refrigerant replacement, reducing both the cost of refrigerant needed and the number of service calls required.

3.5 Conclusions

With timely U.S. ratification of Kigali, residential air conditioning consumers in 2029 are expected to see little to no change in the lifetime costs of purchasing and operating their units. At expected refrigerant prices, they will see a small net savings. At five times that refrigerant price they would see an equally small net cost. On a discounted basis, they would see a cost of less than 1%. These results also assume conservatively that new equipment price is increased by 10% for compliance with Kigali, although such an increase is not justified by historical equipment pricing trends.

Commercial air conditioning consumers in 2029 can expect a similar cost outlook with Kigali ratification. At expected refrigerant prices, lifetime costs, discounted or undiscounted are expected to be reduced by less than one percent. Even with a refrigerant price five times higher than expected, undiscounted total life cycle costs would retain a small net benefit. On a discounted basis, the five times higher refrigerant price would slightly increase costs.

In all of the smaller applications assessed, the cost impact of Kigali ratification on consumers is minimal, and in many cases, consumers will see a net benefit, either from a transition to a less costly material such as a hydrocarbon or from improved energy efficiency, reduced charge size, and reduced leak rates. Consumers in some segments also benefit from the increased competition where manufacturers have already begun to convert some of their products.

[30] See Navigant (2018)
[31] OEM discussions.

4 Summary

The Kigali Amendment to the Montreal Protocol would reduce global use of HFCs by 85% by 2047, replacing them with next-generation hydrofluoroolefins and other products. This Amendment is subject to Senate ratification in the U.S. but will formally take effect globally on January 1, 2019 whether or not the U.S. ratifies. An important consideration in the ratification decision is the impact of the Amendment's requirements on the U.S. economy, both the health of the industries employing HFCs in their current products and the costs or benefits to U.S. consumers.

U.S. industry expects to be more competitive in global markets with Kigali implementation in the U.S. There is strong support for Kigali among the businesses in this industry. A prior study showed that, for the largest sector, HVACR, adoption of the Kigali requirements would increase domestic suppliers' share of the U.S. market over time compared to a future without Kigali. It also showed a pattern of increases in exports over time. Together, these two sources of additional demand supported increased domestic production, jobs, and wages. These jobs and other benefits derived from increased production, not increased prices for products and services in the U.S.

To better understand the effects on consumers, we have analyzed first the considerations faced by manufacturers, either to comply with Kigali's requirements or to operate in a situation where Kigali is implemented elsewhere but not in the U.S. Those decisions will define the market for U.S. consumers. To examine consumer impacts, we then considered the purchasing options for consumers in the two scenarios.

For a detailed study of two of the largest markets, residential and commercial air conditioning, we examined purchases, in 2029, of nominal 2.5-ton and 15-ton air conditioners, using average market cost parameters for each scenario, with and without Kigali ratification. We also examined the characteristics of other market segments to estimate qualitatively the impacts on consumer costs.

Ratification and implementation of the Kigali Amendment in the U.S. allows U.S. industries to address the domestic market in concert with the rest of the world, leading with domestic production rather than focusing their efforts on international investments. This can be accomplished without an increase in costs to the U.S. consumer, and in some cases can generate savings. Although there is no reason to expect that refrigerant prices will behave differently during the Kigali transition than during the two previous transitions away from ozone-depleting substances, even a price higher by a factor of five would not significantly change these conclusions.

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Appendix

A.1 Kigali Amendment Ratifying Countries

Table A.1 provides a list of the countries that have ratified (or otherwise approved) the Kigali Amendment, along with their dates of ratification

Table A.1 List of Kigali Amendment Ratifying Countries

Country	Date	Country	Date
Austria	9/27/18	Lao People's Democratic Republic	11/16/17
Australia	10/27/17	Luxembourg	11/16/17
Barbados	4/19/18	Malawi	11/21/17
Belgium	6/4/18	Maldives	11/13/17
Benin	3/19/18	Mali	3/31/17
Bulgaria	5/1/18	Marshall Isalnds	3/31/17
Burkina Faso	5/1/18	Mexico	9/25/18
Canada	11/3/17	Micronesia (Federated States of)	5/12/17
Chile	9/19/17	Netherlands	2/8/18
Comoros	11/16/17	Niger	8/29/18
Costa Rica	5/23/18	Niue	4/24/18
Ca te d'Ivoire	11/29/17	Norway	9/6/17
Czech Republic	9/27/18	Palau	8/29/17
Democratic People's of Korea	9/21/17	Panama	9/28/18
Ecuador	1/22/18	Portugal	7/17/18
Estonia	9/27/18	Rwanda	5/25/17
European Union	9/26/18	Samoa	3/23/18
Finland	11/14/17	Senegal	8/31/18
France	3/29/18	Slovakia	11/16/17
Gabon	2/28/18	Sri Lanka	9/28/18
Germany	11/16/17	Sweden	11/17/17
Greece	10/5/18	Togo	3/8/18
Grenada	5/29/18	Tonga	9/17/18
Guinea-Bissau	10/22/18	Trinidad and Tabago	11/17/17
Hungary	9/14/18	Tuvalu	9/21/17
Ireland	3/12/18	United Kingdom of Great Britian	11/14/17
Kiribati	10/26/18	Uganda	6/21/18
Latvia	8/17/18	Uruguay	9/12/18
Lithuania	7/24/18	Vanatu	4/20/18

A.2 Kigali Specified Controlled Substances

Table A.2 provides a list of the substances specifically mentioned in the Annex to the Montreal Protocol in relation to the Kigali amendment. The table provides the common substance name and the 100-year global warming potential (GWP).[32]

Table A.2 Annex F to the Montreal Protocol

HFCs (Group I)		**HCFCs**	
Substance	**GWP value (100 year)**	**Substance**	**GWP value (100 year)**
HFC-134	1100	HCFC-21	151
HFC-134a	1430	HCFC-22	1810
HFC-143	353	HCFC-123	77
HFC-245fa	1030	HCFC-124	609
HFC-365mfc	794	HCFC-141b	725
HFC-227ea	3220	HCFC-142b	2310
HFC-236cb	1340	HCFC-225ca	122
HFC-236ea	1370	HCFC-225cb	595
HFC-236fa	9810		
HFC-245ca	693	**CFCs**	
HFC-43-10mee	1640	**Substance**	**GWP value**
HFC-32	675	CFC-11	4750
HFC-125	3500	CFC-12	10 900
HFC-143a	4470	CFC-113	6130
HFC-41	92	CFC-114	10 000
HFC-152	53	CFC-115	7370
HFC-152a	124		
HFCs (Group II)			
HFC-23	14 800		

[32] Source: Polonara et al. (2017).

A.3 Principal Investigators

Joseph M. Steed was architect and lead implementer of DuPont's corporate response to stratospheric ozone depletion concerns during the 1980s, including the ultimate science-based decision to lead the global industry in committing to complete phase-out of CFC production in advance of regulatory requirements. He is an expert in developing broad industry and government support for economically driven international and domestic regulations that achieve a smooth transition for customers.

He has over 20 years of experience as a leader of strategic change in diverse industries and organizations. As CEO of startup International Titanium Powder, LLC, Dr. Steed built on both technical and business background to develop business and financial plans and successfully initiate the transition from development toward commercial operation. As Manager of e-Ventures at DuPont, Dr. Steed served as a catalyst to drive profitable adoption by business leaders of internet transaction tools.

Lent by DuPont to the chemical industry-financed marketplace startup Elemica, Inc., Dr. Steed led marketing strategy, segmentation, customer relationship management (CRM) strategy, and branding for a successful startup that has now outlasted the majority of its imitators. Dr. Steed led Global Strategic Planning for a $2 billion DuPont business, implementing a strategic redirection toward higher value offerings, with a modern ERP infrastructure to drive cost efficiency and customer service. In technology, Dr. Steed led process R&D for a major business resulting in implementation of proprietary and highly profitable cost reductions, waste reduction programs, and novel feedstocks. As Corporate R&D Planning Manager, Dr. Steed drove corporate growth through a funding mechanism for entrepreneurial developments and effective networking of new business development leaders across the corporation.

He also served as a general manager at the technology development company EarthShell Corporation. His recent consulting includes work with the private equity firm Texas Pacific Group, providing chemical industry expertise to assist in their evaluation of a $1B+ buyout. He also served as a principal in a project for AHRI to design a mechanism for stimulating the rate of recycle of HFCs and HCFCs in the United States. Dr. Steed has a Ph.D. in Chemical Physics from Harvard and Sc.B. and Sc.M. degrees from Brown, along with executive training from Columbia's Graduate School of Business. He has published numerous peer-reviewed technical articles and book chapters, including both atmospheric modeling and estimates of global CFC emissions.

Douglas S. Meade is the executive director of Inforum (**In**terindustry **For**ecasting at the **U**niversity of **M**aryland). Dr. Meade has over 30 years of experience in private sector and government in the areas of econometric modeling, economic analysis, and the development of economic data. He was the principal investigator for a previous study done for AHRI, analyzing the national and state level contribution of the HVAC industries within the U.S. economy. Dr. Meade also has extensive experience in international modeling, having helped develop the Inforum bilateral trade model, as well as developing and performing studies with models of Japan, Vietnam, Ukraine, Tanzania, North Korea, and Myanmar.

Prior to his current period at Inforum, he was Deputy Directory of the Industry Division at the Bureau of Economic Analysis, where he was responsible for the development of the 2002 benchmark input-output table. Other previous experience includes work with Data Resources, Inc., an econometric consulting firm which is now part of IHS Global, and with the Census Bureau, serving a research function in the development of manufacturing statistics. He received his B.S. in Economics from George Mason University in 1980, and his Ph.D. in Economics from the University of Maryland in 1990.

Troy A. Wittek graduated with a Criminal Justice degree from the University of Maryland in 2007. He completed a master's degree in Applied Information Technology from Towson University in 2012. He joined Inforum in 2006 and became a full-time Research Assistant in 2009. Troy's responsibilities include collecting and analyzing statistical data for use in policy analysis, business planning, and academic research. He has helped to write and edit reports for a variety of audiences in the academic, government, and private sectors. Troy is one of the main researchers responsible for maintaining the Inforum *Lift* and *Iliad* models of the U.S. economy. He works with the Department of Defense to project defense purchases and skilled labor requirements by industry and by region using Inforum economic models. Other projects include providing forecasts for domestic industries and analyzing the impact of major soft drink bottler operations in Asia. Additional responsibilities include literature review, software testing, and website development.