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ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Benefits and Challenges in Using Low GWP A3 Refrigerants in Residential Air Conditioning Equipment

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PREPARED BY:

Max Wei Greg Rosenquist Katie Coughlin
Ed Cubero Chao Ding Tom Burke
Lawrence Berkeley National Laboratory

Omar Abdelaziz*
The American University in Cairo, Cairo, Egypt
Primary Authors

Jackson Thach
Project Manager
California Energy Commission

Agreement Number: EPC-16-041

Anthony Ng
Branch Manager
Technology Innovation and Entrepreneurship Branch

Jonah Steinbuck, Ph.D.
Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Benefits and Challenges in Deployment of Low GWP A3 Refrigerants in Residential Air Conditioning Equipment is the final report for the project name project (Contract Number EPC-16-041) conducted by the Lawrence Berkeley National Laboratory. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

Propane gas is a very low-global warming potential refrigerant that provides good cooling equipment performance. The flammability of propane, however, makes the management of equipment design, handling, and maintenance critical factors to ensure that any cooling equipment with propane refrigerant is safe to use across a product's lifetime. Flammable refrigerants are mostly used in units with small cooling capacity, particularly in factory-sealed units since these have the lowest risk of refrigerant leakage.

This project focused on the potential climate benefits and costs of transitioning to propane refrigerant in three types of small-room air conditioning units (window air conditioning, packaged terminal air conditioning/heat pumps, and mini-split heat pumps). The team modeled optimized designs, tested results of these types of air conditioning units with propane, and estimated net impacts to greenhouse gas emissions and consumer costs for California over the next three decades.

Modeled results show that small air conditioners have the highest market favorability and the ability to meet refrigerant quantity limits (per unit) set by United States Environmental Protection Agency in 2015. Between 15 and 66 million metric tons of greenhouse gas savings were estimated if these three types of air conditioning units shifted to propane refrigerant between 2022 and 2051, compared to using baseline refrigerant R-32 and R-410A, respectively. An estimated savings of $44.50 per ton of carbon dioxide equivalent is possible due to lower operating costs of R-290 due to higher energy efficiency than baseline refrigerants.

Keywords: room air conditioning, low GWP sector, HFCs, alternative refrigerants, propane refrigerant, R-290, window air conditioner, packaged terminal air conditioner, mini-split air conditioner

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Executive Summary

Introduction

High-global warming potential (GWP) refrigerants are the fastest growing sector of greenhouse gas (GHG) emissions in the world. They are primarily used in both refrigeration and cooling equipment. Hydrofluorocarbon refrigerants are the main high-GWP gases, with values thousands of times greater than carbon dioxide on a pound-for-pound basis (1400 to 3000 times more potent than an equivalent weight of carbon dioxide in air conditioning equipment). To meet California's aggressive climate mandates of 40 percent lower GHGs in 2030 from high-GWP gases (relative to 2013), additional measures are required.

Propane is a very a low-GWP refrigerant (only four times more potent than an equivalent weight of carbon dioxide) and offers equivalent-to-better energy efficiency compared to high-GWP, hydrofluorocarbon-based refrigerants. Propane could potentially reduce GHGs in the high-GWP sector in cooling equipment such as small air conditioning (AC) systems and small factory sealed (self-contained) refrigeration and air conditioning units such as window AC units. However, as a hydrocarbon gas, propane is highly flammable and when used as a refrigerant typically operates at higher pressures than other household uses of propane, such as propane-fueled outdoor grills.

More characterizations and analyses are needed for low-GWP refrigerants such as flammable hydrocarbon-based refrigerants. Findings from this project could offer pathways to greater GHG emission reductions from high-GWP gases since they include the deeper exploration of the benefits, costs, and risks of propane refrigerant.

Project Purpose

The project purpose was to:

- Quantify the potential costs and GHG savings of transitioning to propane (R-290) refrigerant in small AC equipment in California.
- Identify promising products and application areas.
- Summarize safety features required for the design of R-290 AC equipment and the safe handling of R-290.
- Identify regulatory barriers and key areas for technology improvements.

The project scope for modeling, testing, and cost analysis was limited to small AC and heat pumps using propane. These types of products are already achieving practical acceptance internationally, though larger AC or refrigeration units with propane face more onerous technical and regulatory barriers.

Audiences for this report include policy makers, regulators (for example, the California Air Resources Board and the United States Environmental Protection Agency), standard setting agencies (American Society of Heating, Refrigerating and Air-Conditioning Engineers and the Underwriters Laboratory) and air conditioning equipment manufacturers.

Project Approach

The team includes researchers at Lawrence Berkeley National Laboratory, with co-funding support provided by the International Energy Analysis Department at the American University of Cairo for equipment modeling development, equipment performance benchmarking, and policy analysis. Additionally, a technical advisory committee was formed and included regulators from the California Air Resources Board, industrial experts, and technical experts to provide feedback on the project results.

The research was organized around three key themes: (1) assessing the current market, and the technical and regulatory status for refrigeration and cooling equipment with hydrocarbon refrigerants; (2) testing the energy efficiency and capacity of small AC units with R-290 compared with another refrigerant (R-22 or freon); and (3) modeling the potential cost and GHG reduction savings for transitioning to R-290 refrigerants in small ACs over the next 30 years. For the equipment testing, the team procured six, small AC units that use R-22, which has similar refrigerant properties to R-290 and compatible equipment components such as compressors.

To perform the equipment testing, the Lawrence Berkeley National Laboratory Air Conditioner and Heat Pump test facility was configured for the safe handling and testing of R-290 flammable refrigerant. The testing included detecting and purging flammable gas from the system, shorter line lengths that minimize the risk of refrigerant leaks, managing refrigerant pressures in packaged terminal AC and window AC units, and managing R-290 supply and disposal. Some delays to equipment testing were incurred by the lab shutdown during the COVID-19 pandemic, so methods for testing were modified and automated so that testing could proceed with limited staff during that time.

Project Results

The research demonstrated that propane is an attractive refrigerant from a cost and GHG emissions-reduction standpoint, and that among small AC product types, window ACs are most suited for small room ACs with propane. Testing results show that window AC units with 1-ton cooling capacity or less using R-290 could meet the refrigerant quantity limit set by the United States Environmental Protection Agency in 2015. Small self-contained units are also at lower risk for refrigerant leakage and flammability than non-self-contained units such as mini-split units, which typically have an indoor air handling/evaporator unit and an outdoor compressor/condenser unit, with a refrigerant line running between them. The economic analysis showed that the cost of switching to propane for small ACs is a minimal additional cost but delivers substantial reductions in direct GHG when compared to baseline HFC refrigerants.

Propane is less favorable in packaged terminal AC/heat pump units since these units are typically installed lower to the ground so the refrigerant charge has a greater tendency to pool on the ground, increasing the risk of combustion from sparks or other combustion sources. Propane is heavier than air, which means that if a leak occurs in equipment mounted close the floor it could pool and lead to higher risk). Under United States Environmental Protection Agency regulations, R-290 is not allowed in charged units installed in the field, so is therefore not allowed in mini-splits. Installation and refrigerant leakage are less of a concern in self-contained equipment.

Modeling Results: Numerical models for small air conditioning units were developed to better understand the energy performance of air conditioner systems from both system and component levels. The modeling shows high potential for improved energy efficiency by switching to propane. The optimal window AC achieves 24 percent energy efficiency while the optimal mini-split AC achieves 20 percent efficiency when compared with a reference R-22 refrigerant.

Incremental Equipment Cost Analysis Results: Manufacturing cost for room AC equipment is expected to be a few percent higher when compared to designs with conventional R-22 refrigerants, with an upper bound of 7-percent higher cost (with the incorporation of primary and back-up safety systems).

Testing Results: Propane is a flammable refrigerant with equivalent or improved energy efficiency performance relative to reference equipment with R-22 (freon) refrigerant. Results indicate that optimally designed window air conditioners could meet the current United States Environmental Protection Agency maximum of allowable propane weight.

Life-Cycle Cost Analysis: For each of the three products, the life-cycle cost (or the purchase cost and operating costs across a unit's lifetime) was calculated for a large population of consumers. The switch to propane resulted in a 1 to 2 percent increase in life-cycle costs. In dollar terms, this incremental cost range is $25 to $75 when compared to overall life-cycle cost analyses, on the order of one to several thousand dollars. These incremental costs are low enough for the state to potentially provide consumer rebates or subsidies to cover those increased costs. Implementation of such a program of subsidies was used to calculate a cost of carbon dioxide equivalent (CO_2e) savings, as described in the Net Impact Analysis section.

Net Impact Analysis: The net impact to greenhouse gas emissions and their cost impacts are estimated for a full transition to propane refrigerants over a 30-year period for window air conditioners, packaged terminal AC/heat pumps, and mini-split heat pumps when compared to the baseline refrigerant (R-410A).[1] most commonly used for room air conditioners (assuming equivalent energy efficiency for propane refrigerant).

The additional equipment cost over the 30-year time frame is estimated to be $452 million, with greenhouse gas reduction savings of 61.9 million metric tons of CO_2e, compared to R-410A. This corresponds to a cost per ton-CO_2e saved of $7.31 which is relatively low cost for CO_2e emission reductions. The research team also performed sensitivity cases, where in the best case of 10 percent energy efficiency improvement from propane, there was a negative cost of CO_2 saved, or a savings of $44.52 per ton of CO_2e saved.

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[1] For energy efficiency (EE) and modeling, R-22 was used because the units for testing had R-22 baseline. The models for energy efficiency improvements were then calibrated to this R-22 test data. The reasons R-22 units were used for testing is that R-290 can be dropped into those units. R-290 cannot be dropped into R-410A units since the compressor design is incompatible with it.

In contrast, for national impact analysis and cost, R-410A was used since room ACs have already moved on from R-22 to R-410A, as R-22 (freon) is an ozone depleting HCFC phased out under the Montreal Protocol.

Based on empirical and modeled findings in the literature the EE performance of R-22 unit and R-410A unit are very similar at the at the rated cooling condition (95°F [35°C]) (e.g. Payne and Domanski, 2002).

Advancing the Research to Market

The team has shared results of this study with the California Air Resources Board to encourage a regulatory approval path for R-290 units by safety standards bodies such as Underwriters Laboratories and AC vendors and compressor manufacturers, and presented project results at a California Energy Commission workshop entitled Building Decarbonization and Refrigerants, August 26, 2021, for stakeholders from both the California Public Utilities Commission and industry.

Lawrence Berkeley National Laboratory anticipates publishing the results of this analysis in a journal, with publication expected in 2024. This will make the data, methods, and results of this work broadly available to research, development, and deployment to communities on national and international levels. In addition to communicating and archiving the key findings of this work to a wider audience, this publication will also provide an opportunity to highlight to other RD&D stakeholders key areas and opportunities for further reductions and other important areas for follow-up work (for example, lower cost, higher energy efficiency designs, and market development programs).

Benefits to California

High-GWP refrigerants are the fastest growing source of GHG emissions, so cost-effective approaches to sharply reduce emissions in this sector are urgently needed. With a warming climate, climate-friendly and energy-efficient small AC units are even more important. Climate friendly and cost-effective AC are also important to support the state's goals for more climate equity and greater resilience in increasingly frequent, high-demand extreme heat waves.

This technology demonstrates that room air conditioners with propane refrigerant (R-290) could potentially achieve substantial GHG savings and a low cost per ton of CO_2e saved at an estimated $14.50 or less per ton of saved CO_2e to $44.50 per ton over a 30-year time frame.

Small window air conditioning units with R-290 refrigerants can be readily adapted to a small commercial building or residential home. Estimated high-end costs total an average increase of $26 to the purchase price of the unit, which corresponds to a small 3.2 percent increase in overall cost across the product's lifetime.

Introducing room AC units with propane refrigerants into the market would give consumers greater choice when choosing climate-friendly AC equipment. Room ACs with propane would reduce CO_2e emissions from the refrigerant over 99 percent compared to current baseline refrigerant gases due to propane's much lower global warming potential.

CHAPTER 1: Introduction

Background

High-global warming potential (GWP) refrigerants are the fastest growing area of greenhouse gases (GHG) in California and are primarily used as heat exchange media in refrigeration equipment and air conditioning and heat pump equipment in addition to other uses such as spray foams and fire extinguishers. Current baseline refrigerant gases are hydrofluorocarbons (HFCs). Unlike the previous class of refrigerants (hydrochlorofluorocarbons [HCFCs]) and chlorofluorocarbons [CFCs]) that were phased out under the 1987 Montreal Protocol, HFCs are non-ozone destroying substances. However, HFCs have high global warming potential, specifically the impact to global warming of HFCs typically ranges from a few hundred to thousands of times more potent than an equivalent mass of carbon dioxide, on a 100-year time horizon. HFCs, along with methane and nitrous oxide, have shorter residence times in the atmosphere than carbon dioxide (CO_2), so are thus known collectively as short-lived climate pollutants. Typically, HFCs are released to the atmosphere during their production, transport, use in the field from refrigerant leakage from heating, ventilation, air conditioning (HVAC) equipment, and end-of-life release. The last two sources are usually the dominant sources of HFC emissions.

Figure 1(a) shows GHG emissions by sector in California from 2000 to 2018. High-GWP gases were 20 million metric tonnes of carbon dioxide equivalents (MMT CO_2e) per year in 2018 and are the fastest growing GHG sector (CARB, 2020a). This represents 4.7 percent of the 425 MMT CO_2e total emissions in 2018. Figure 1(b) shows HFC emissions in California (CARB, 2020b). These constitute 98 percent of GHGs from the high-GWP gases sector. Stationary AC is projected to grow from 34 percent to 46 percent of total high-GWP gases emissions by 2030.

Figure 1(a): GHG Emissions by Sector in California From 2000 to 2018

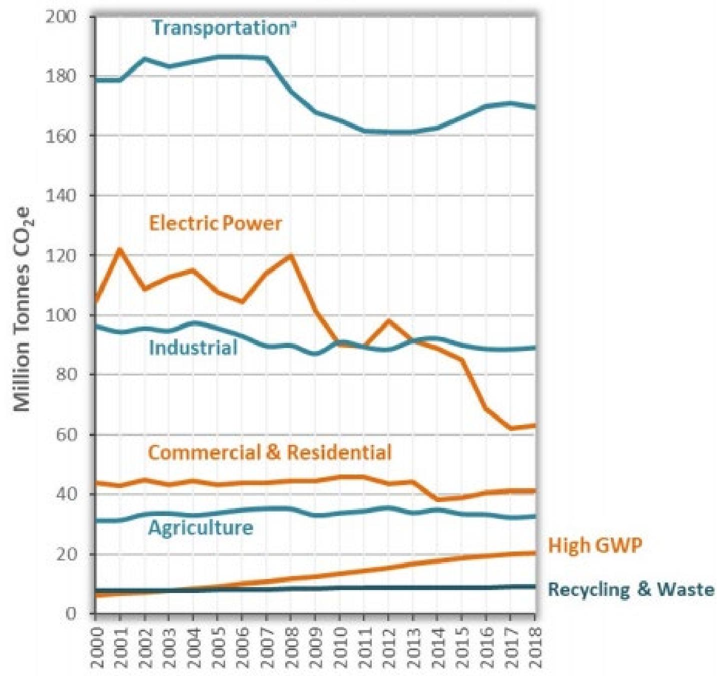
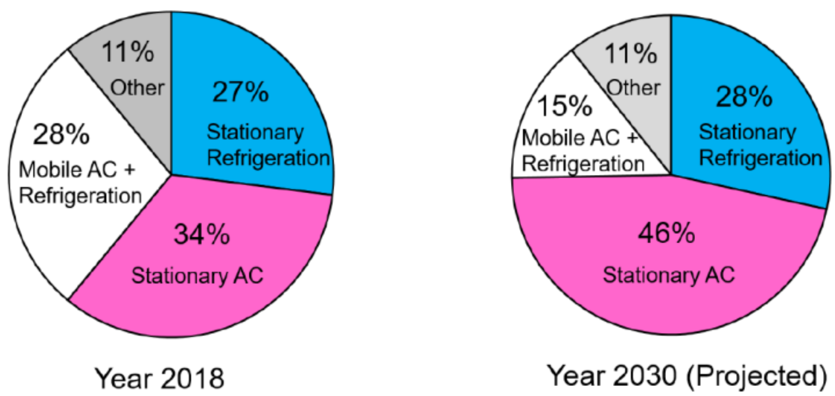


Figure 1(b): HFC Emissions in California in 2018 and Projected Emissions in 2030



Source: a) CARB 2020a, b) CARB F-Gas Inventory, 2017

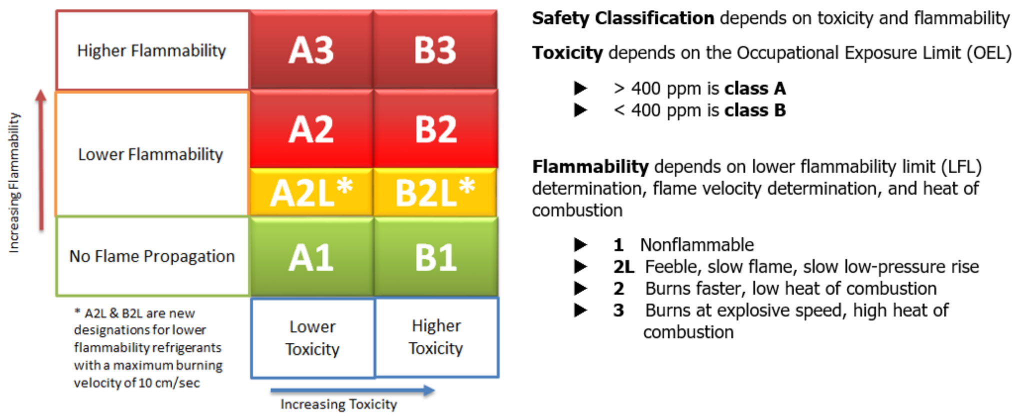
Refrigerant Types and Sources for Refrigerant GHG Emissions

Commonly used HFC refrigerants today are classified as "A1" (or non-flammable), with low toxicity per American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard 34-2019, and are used in a variety of applications including refrigeration and air conditioning equipment, foam insulation, and fire suppressants. Though these HFC refrigerants are non-ozone depleting substances (non-ODS), they are high-GWP refrigerants with GWP values hundreds to thousands of times more potent than CO_2 (for example, R-134A, R-404A, and R-410A have GWP values of 1430, 3922, and 2088, respectively).

Many low- or lower-GWP refrigerant alternatives are "mildly flammable" (A2L classification) or "flammable" (A3 classification) where Class 2L versus 3 flammability classifications are based on two criteria (Figure 2):

- Burning velocity,[2] or the maximum velocity at which a flame spreads in a normal direction relative to unburned gas ahead of it
- Heat of combustion[3]
- Lower flammability limit[4] (ASHRAE, 2019)

Figure 2: Table of Refrigerant Classifications



Source: ASHRAE 2019

Current HFC-based refrigerants are Class A1 (non-flammable, lower toxicity), while most lower-GWP refrigerants (GWP<750) for air conditioning are Class A2L (mildly flammable, lower toxicity) or Class A3 (flammable, lower toxicity). Alternatives to the HFC refrigerant, R-410A, commonly used in air conditioning systems tested in the Air Conditioning, Heating, and Refrigeration Institute's (AHRI) *Low-GWP Alternative Refrigerants Evaluation Program* are shown in Table 1. All are classified as A2L or mildly flammable, non-toxic refrigerants. AHRI and others have also conducted tests for R-290 (GWP=3.3) as an alternative refrigerant to HFCs.

Table 1: Alternative Refrigerants Tested

AHRI Testing Phase 1 or Phase 2	Alternative Refrigerant to R-410A	Composition	(Mass%)	Classification (Note 1)	GWP100 (Note 2)
1	ARM-70a	R-32/R-134a/R-1234yf	(50/10/40)	A2L	482
1	D2Y60	R-32/R-1234yf	(40/60)	A2L	272
1	DR-5	R-32/R-1234yf	(72.5/27.5)	A2L	490

[2] Mildly flammable refrigerants, class 2L are characterized by a burning velocity <10 centimeters per second (cm/s).

[3] The heat of combustion of a substance is the energy released when a specified amount (e.g. 1 mole, 1 gram, 1 liter) of the substance burns completely in oxygen. The heat of combustion is usually measured at conditions 298K (77°F [25°C]) and 101.3 kilopascal.

[4] Lower flammability limit (percent by volume or grams per cubic meters [g/m^3]) is the minimum concentration of the refrigerant that is capable of propagating a flame through a homogeneous mixture of the refrigerant and air.

AHRI Testing Phase 1 or Phase 2	Alternative Refrigerant to R-410A	Composition	(Mass%)	Classification (Note 1)	GWP100 (Note 2)
1	HPR1D	R-32/R-744/R-1234ze(E)	(60/6/34)	A2L	407
1	L41a	R-32/R-1234yf/R-1234ze(E)	(73/15/12)	A2L	494
1	L41b	R-32/R-1234ze(E)	(73/27)	A2L	494
1	R-32	R-32	100	A2L	675
1	R-32/R-134a	R-32/R-134a	(95/5)	A2L	713
1	R-32/R-152a	R-32/R-152a	(95/5)	A2L	647
2	ARM-71a	R-32/R-1234yf/R-1234ze(E)	68/26/6	A2L	460
2	DR-5A (R-454B)	R-32/R-1234yf	68.9/31.1	A2L	466
2	DR-55	R-32/R-125/R-1234yf	67/7/26	A2L	698
2	HPR2A	R-32/134a/1234ze(E)	76/6/18	A2L	600
2	L-41-1 (R-446A)	R-32/R-1234ze/Butane	68/29/3	A2L	461
2	L-41-2 (R-447A)	R-32/R-1234ze/R-125	68/28.5/3.5	A2L	583

Testing done under AHRI's low-GWP *Alternate Refrigerant Evaluation Program*, Phase 1 and Phase 2

Source: Wang and Amrane 2014, 2016

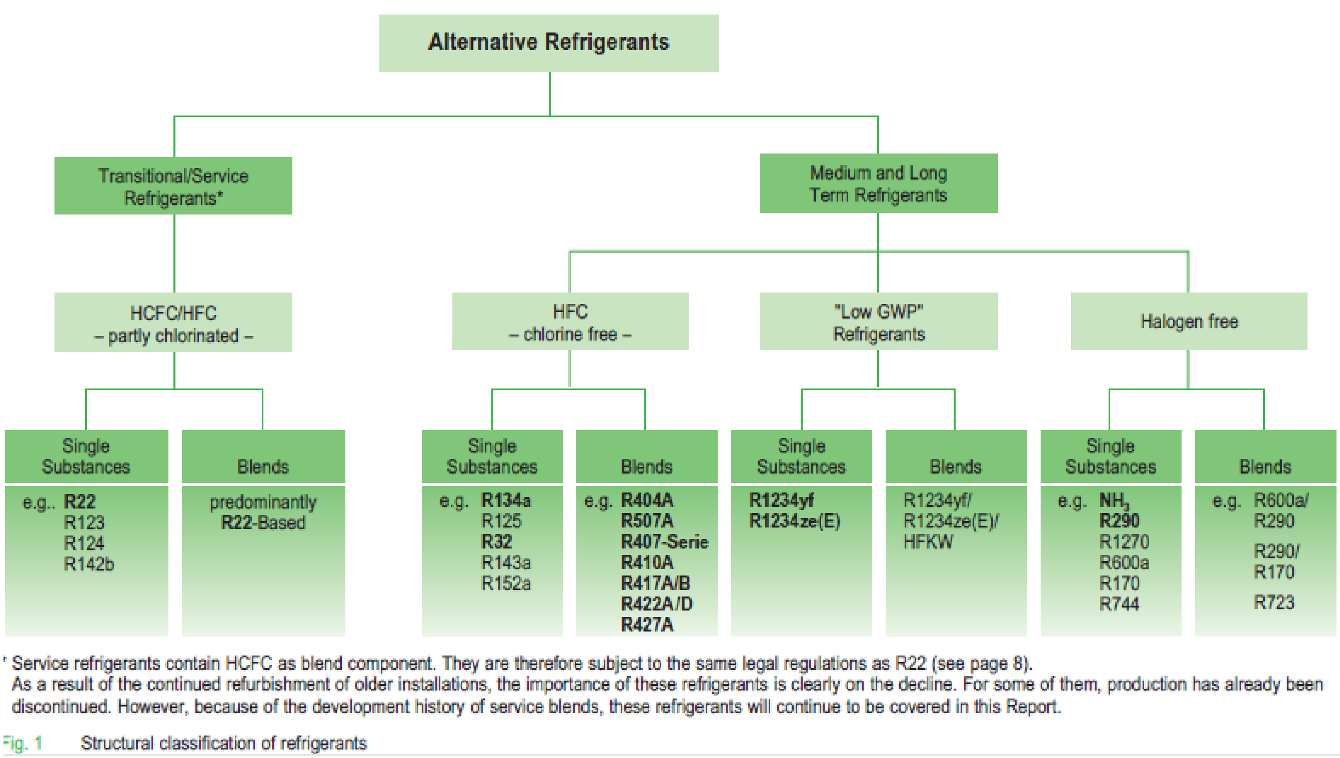
The development of alternative refrigerants with much lower-GWP values than HFCs is an active area of research. Types of refrigerant (Figure 3) that are non-ozone destroying and "low-GWP refrigerants" include hydrofluoroolefins (HFOs) and HFO blends such as R1234yf and R1234yf blends and halogen-free refrigerants such as ammonia, hydrocarbons (propane=R-290; propylene=R1270; isobutane=R600a) and CO_2 itself. This last category is also referred to as "natural refrigerants." Each of these refrigerant choices has tradeoffs in environmental impact, component impacts (heat exchangers, compressors), and system cost (Wan et al., 2021). For example, ammonia is a Class B2L refrigerant because of toxicity and flammability concerns, and HFOs are not as thermodynamically efficient as R-290 and are more expensive than hydrocarbon refrigerants.

The research and development challenge for new refrigerants is that the new refrigerant has suitable refrigerant performance and attributes in heating and cooling equipment and can be manufactured and used safely. For example, many lower-GWP refrigerant alternatives for air conditioning systems are mildly flammable (or Class A2L) refrigerants that require specific safety standards for handling and equipment maintenance.

Before an alternative flammable or mildly flammable refrigerant can be introduced into the market, safety standards must be developed and approved (such as Underwriters Laboratory [UL] or ASHRAE or both) and other relevant review bodies must develop their own standards such as the fire marshal and other authorities with jurisdiction (such as local building codes), before these standards can be included in California building codes.

The development of targets and goals for California to reduce GHG emissions from HFCs are thus dependent on the readiness of alternative refrigerants as well as the maturity of corresponding safety standards

Figure 3: Typology of Refrigerant Options



Source: Bitzer 2021

Some refrigerant vendors have recently announced the availability of Class A1 refrigerants for air conditioning. For example, the new refrigerant R-466 is an A1 refrigerant with a lower GWP (733) and is a blend of R-32 and R-125 with 39.5 percent of CF3I, a fire suppressant (trifluoroiodomethane) (Cooling Post 2019). This refrigerant has a small but non-zero ozone depleting potential (ODP) though it has historically limited production and iodine supplies. The short-term replacements for R-410A remain to be determined, with R-32 as a leading candidate, but the longer-term future will be more GHG-constrained with more environmentally friendly refrigerants likely to be required.

Sources of GHG emissions from refrigerant gases include direct and indirect emissions. Direct sources include refrigerant leakage during manufacturing, distribution, and installation during both equipment operation and operating lifetime and any refrigerant loss during end-of-life disposal. This report will account for two of these sources: annual operating losses as a percentage of the initial refrigerant charge quantity, and end-of-life refrigerant loss as a percentage of the initial refrigerant charge quantity.

Indirect emissions are GHG emissions from electricity generation that powers the cooling equipment. This source of emissions is higher in regions of the United States with higher fractions of fossil fuel-derived electricity, and lower in regions like California, which has a higher fraction of renewable energy sources. In general, the relative lifetime contribution of indirect emissions is greater than direct emissions, but as the electricity grid in California nears zero carbon, the relative fraction of direct emissions increases and becomes the dominant portion of GHGs from cooling equipment. Terms used to describe lifetime GHG emissions associated with cooling equipment include life cycle climate performance and total equivalent warming impact.

Since high-GWP gases are the fastest growing sector of GHGs in both California and the world, there are major policies in California and internationally to both aggressively phase down the use of HFCs and to replace them with non-ODS low- (or lower-) GWP refrigerants.[5]

Policies

Internationally, the Kigali Amendment to the Montreal Protocol was approved in 2016 as part of the United Nations Environmental Program *Meeting of the Parties,* which entered into force on January 1, 2019 (assuming ratification by at least 20 parties). The goal is to achieve over 80 percent reduction in HFC consumption by 2047. As of April 16, 2021, 119 states and the European Union have ratified the Kigali Amendment but does not include the United States. Internationally, the Kigali Amendment phases down the consumption of HFCs by 85 percent in developed countries by 2036, with less strict requirements for developing countries.

In the U.S., the American Innovation and Manufacturing Act (AIM Act) was passed on December 27, 2020, as part of the Consolidated Appropriations Act, 2021 (Pub. L. 116-260). The AIM Act directs the United States Environmental Protection Agency (U.S. EPA) to phase down HFC production and consumption by 85 percent by 2036, maximize HFC reclamation and minimize HFC releases, and facilitate a transition to next-generation technologies through sector-based restrictions. The HFC phasedown schedule from the AIM Act (Table 2) closely mirrors the Kigali Amendment (Hine, 2021; U.S. EPA, 2021).

Table 2: HFC Phasedown Schedule and Consumption and Production Allowance Caps

Year	Consumption & Production Allowance Caps as a Percentage of Baseline	Estimated Consumption and Production Allowance Caps in MMTEVe*
Proposed Baseline**	**Consumption: 299 MMTEVe Production: 375 MMTEVe**	
2022–2023	90 percent	Consumption: 269.1 Production: 337.5
2024–2028	60 percent	Consumption: 179.4 Production: 225.0
2029–2033	30 percent	Consumption: 89.7 Production: 112.5
2034–2035	20 percent	Consumption: 59.8 Production: 75.0
2036 & after	15 percent	Consumption: 44.9 Production: 56.3

* Baselines are expressed in million metric tons of exchange value equivalent (MMTEVe), which is numerically equivalent to one million metric ton of CO_2 equivalent (MMTCO_2e).
** These proposed baselines are based on currently available data, and the final figures may change based on an evaluation of all available data and information received prior to the final rulemaking. Baseline is based on 2011-2013 average baseline for HFC production and consumption.

Source: U.S. EPA factsheet April 30, 2021

[5] For these purposes, "low-GWP" refrigerants have a GWP value from 1-99 and "lower-GWP" have a GWP value from 100-750, but these are approximate ranges.

On April 2021, the U.S. EPA finalized a list of new refrigerant options that could be used as substitutes and on May 19, 2021, released the first proposed rule under the AIM Act to address HFCs. This rule proposes an initial method for allocating and trading HFC allowances and describes a compliance and enforcement system (U.S. EPA, 2021).

California Policies

The state has aggressive climate targets in place with Senate Bill (SB) 1383. This bill requires 40 percent reduction of HFCs in 2030 relative to the 2013 baseline. Most recently, the California Air Resources Board (CARB) has released rules phasing out high-GWP refrigerants in commercial refrigeration and air conditioning in the next few years.

On December 10, 2020, CARB approved regulations to phase down HFC refrigerant use in commercial and residential AC equipment and commercial and industrial stationary refrigeration units as part of the state's plans to reduce HFC emissions, as mandated by SB 1383 (Table 3).

Table 3: CARB Low-GWP Rules

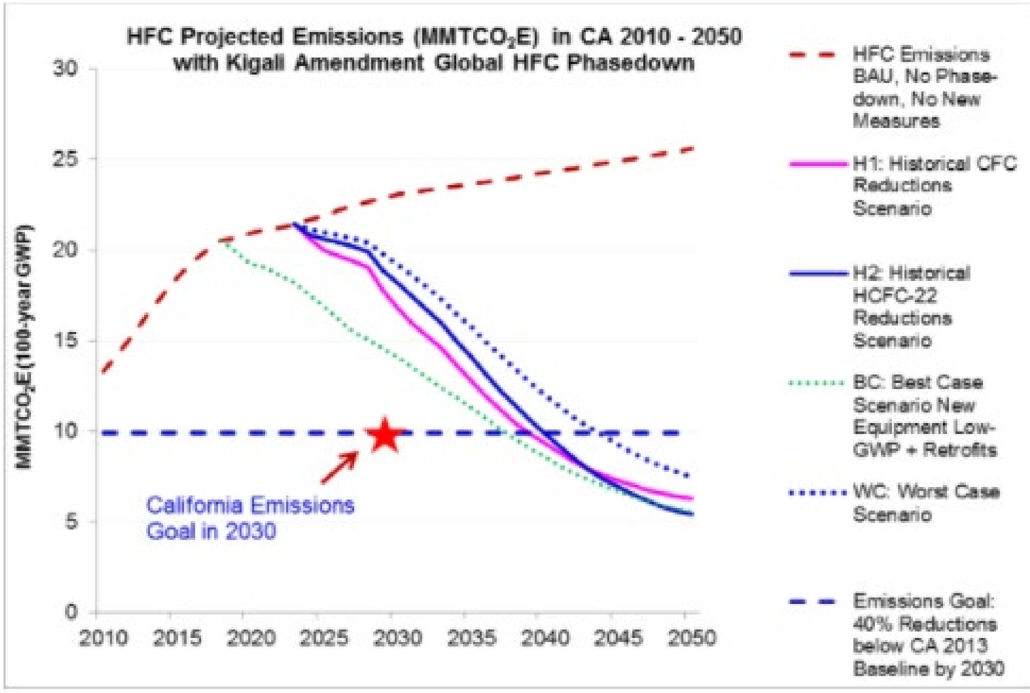
Category	Type of facility of equipment	GWP limit	Starting date of new rule
Commercial refrigeration equipment	New or fully remodeled facilities that utilize new commercial refrigeration equipment containing more than 50 pounds of refrigerant*	150	Jan 1, 2022
Stationary air conditioning equipment	New room air conditioners (RACs) and dehumidifiers	750	Jan 1, 2023
Stationary air conditioning equipment	Larger stationary AC used in residences and commercial/non-residential buildings excluding VRFs	750	Jan 1, 2025
Stationary air conditioning equipment	Variable refrigerant flow (VRF) stationary air conditioning equipment	750	Jan 1, 2026

*In addition, food retailers with 20 or more stores would need to comply with one of two options for existing stores: maintaining a weighted average refrigerant GWP below 2,500 by 2026, or reduce GWP potential (charge size times GWP) by at least 25 percent by 2026. All stores would need to have an average GWP below 1,400 or reduce GWP potential by 55 percent by 2030.

Source: CARB 2020

The CARB report (CARB, 2017) entitled *Meeting the Kigali Amendment Targets* highlighted the challenge for the state to meet the HFC phase-down target of SB 1383 by 2030, assuming the Kigali Amendment (equivalent to the AIM Act goals by 2040) is in force as indicated in Figure 4. Thus, there is the need for more aggressive transitioning across the refrigeration and air conditioning sector with either faster transition to low-GWP refrigerants or a transition to refrigerants with lower GWP values such as propane. There is a lack of studies on the costs and benefits of transitioning the small AC sector to R-290 refrigerant in California.

Figure 4: Estimated HFC Emissions in California from the Kigali Amendment (Equivalent to AIM Act)



Source: CARB 2017

The state has a need for more research and development to support the SB 32 target of 40 percent GHG reduction from 1990 levels and, specifically, to support the SB 1383-mandated HFC reduction targets in 2030. With climate change, AC cooling demand is expected to increase in the state, so reductions in GHG emissions from cooling equipment are essential for the state to meet its targets, including emissions from direct refrigerant leakage and indirect emissions from the electricity grid. Note that SB 1383 is more stringent for fluorinated greenhouse gas reductions than the recently concluded Kigali Amendment to the Montreal Protocol.

Propane as an Alternative Refrigerant

Propane (R-290) is a promising alternative refrigerant that is non-ozone destroying and has a GWP value of 3.3. However, as a flammable substance, it is subject to stringent safety standards; only limited quantities of R-290 are currently allowed per UL safety standards and the U.S. EPA. Propane and other alternative refrigerants (R-32, R-466A, and R-452B) are promising in air conditioning (Wan et al., 2021).

Each alternative refrigerant has strengths and weaknesses based on a wide range of criteria such as environmental impact (for example GWP value, toxicity), compressor impact (for example compressor capacity, glide), heat exchanger impact (such as heat transfer pressure drop), and system impact (such as compressor and system cost) (Wan et al., 2021). For example, a recent simulation shows that for 3-ton unitary air conditioners, R290 has the best performance compared to R-32, R-466A, R-452B, and R-410A (Wan et al., 2021).

As a low-GWP refrigerant with good thermodynamic properties, propane has the potential to reduce direct emissions of refrigerant gases in smaller AC systems, smaller self-contained refrigeration systems, and distributed refrigeration systems with many circuits. However, as a hydrocarbon gas, propane is highly flammable and typically operates at higher pressures than other uses of propane around the household such as propane outdoor grills.

The usable amounts of propane are thus limited to reduce risk of ignition from any leaks and require careful handling and equipment design to minimize the risk of refrigerant loss, and eliminate (where possible) any source of sparks within the equipment.

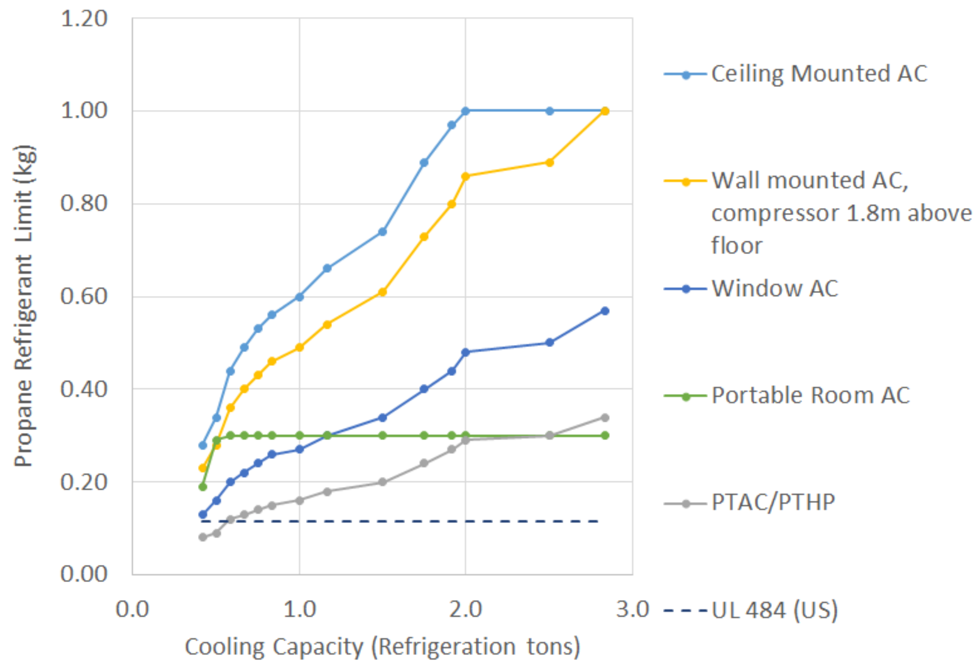
Equipment with A2L and A3 refrigerants require equipment and facility redesign to meet application and safety standards. Propane is most readily adopted in smaller AC and commercial refrigeration equipment (CRE) systems where the unit is self-contained, charge limits are small (for example, less than a few hundred grams) and factory-installed, and risks from ignition are contained, and safety precautions managed, within the factory.

Systems with larger amounts of charge must carefully manage safety risks through a rigorous set of measures such as minimal room size, minimal air flow/ventilation requirements, safety sensors, and temperature/pressure sensors and actuators. In addition, a transition to propane would require updating equipment supplier factories to safely handle flammable gases and additional contractor and technician training to provide sufficient training for the handling, installation, maintenance, and proper disposal of end-of-life equipment.

The U.S. EPA 2015 charge limits for room AC products are shown in Figure 5 along with the UL 484 charge limit. Note that the U.S. EPA's refrigerant quantity limit for propane is a function of cooling capacity and there is a progression of acceptable charge sizes, which increase more or less proportionally with the height at which the equipment is typically installed. Product types closest to the floor such as packaged terminal AC/heat pumps (PTAC/PTHP) and portable room AC have the lowest allowable refrigerant charge limits, while those at the highest height have the highest allowable refrigerant charge limits. The UL484 limitation of 114 grams for A3 refrigerants in room ACs (UL, 2017) effectively precludes the use of propane in all but the smallest window AC (such as Shen and Fricke 2019) and PTAC/PTHP units.

The International Electrotechnical Commission (IEC) update to the safety standard (IEC, 2021) to allow higher quantities of flammable refrigerants in room AC systems, heat pumps, and dehumidifiers, was released in May 2022. The proposed update to the safety standard would increase allowable charge sizes, subject to additional requirements. For example, charge sizes of up to 998 grams in split systems would have additional requirements (Garry, 2020) for airflow, safety shutoff valves, tightness testing, and other construction and testing requirements.

Figure 5: U.S. EPA 2015 and UL484 Charge Limits on Air Conditioning Equipment



Sources: U.S. EPA 2015 and UL 2019

Refrigeration

Domestic Refrigeration

In September 2018, the U.S. EPA raised the charge limit for hydrocarbon refrigerants in new home refrigerators and freezers from 57 grams to 150 grams under its *Significant New Alternatives Policy Program*. Full size refrigerators with hydrocarbon refrigerant isobutane (R-600A) are available on the market. In 2022, California banned the use of high-GWP refrigerants like R-134a in full-size refrigerators. Already, 95 percent of refrigerators manufactured in Europe, China, Brazil, and Argentina already use isobutane.

Small Commercial Refrigeration Equipment

For self-contained CRE, equipment with R-290 is commercially available and widely adopted in the United States. True Manufacturing Corporation is a CRE supplier offering many of its CRE with R-290, and plans to have 100 percent of its future equipment R-290 (McLaughlin, 2021).

While the recent IEC ruling has raised R-290's charge limits internationally to 500 grams, current U.S. safety standards still limit applications to 150 grams. Typically, self-contained, R-290 units are charged and hermetically sealed at the manufacturing facility (Emerson, 2020).

Since CRE with propane is already widely available and full-size domestic refrigerators are available, these two product types are out of scope for this project.

CHAPTER 2:
Project Approach

The technical approach described in this chapter for this project was air conditioning energy performance modeling, test procedures, equipment costing, lifecycle costs, and California net impact analysis over the next three decades for GHGs and customer costs.

Approach to AC Energy Performance Modeling

Numerical models for small air conditioning units were developed to better understand the energy performance of the AC systems from a system and component level. The approach here is to develop calibrated AC performance models to characterize AC performance, to identify opportunities for performance improvement through sensitivity studies of key AC parameters, and to find optimal parameter values based on these models.

The key geometries of the AC units are directly measured from the actual products, in this case one window AC unit and one mini-split AC unit. Two industry-standard simulation tools, VapCyc® and CoilDesigner®, are used to develop physics-based models for detailed vapor compression cycle simulation and optimization. The simulation results are compared with the actual products and validated using the test data.

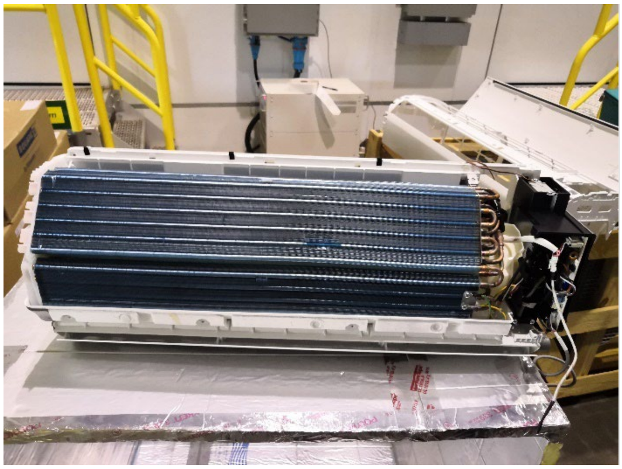
Table 4 summarizes the high-level energy performance information of the selected units. Both have fixed-speed compressors and use R-22 as refrigerant. Figure 6 shows the photos of the selected units.

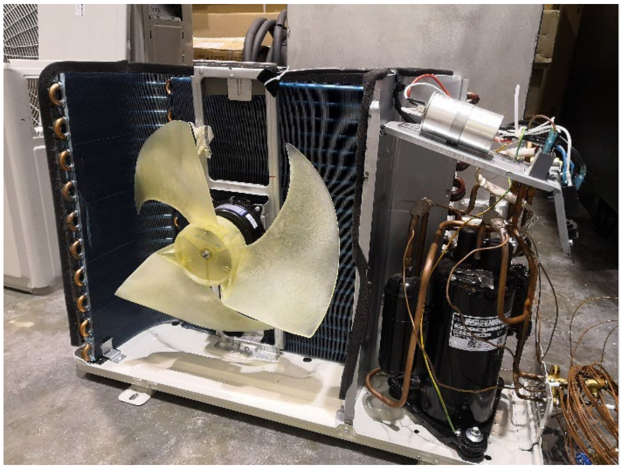
Table 4: Fixed-Speed AC Models

Model #	Product Type	Brand Name	Model Information	Market	Nameplate EER (W/W)	Nameplate Cooling Capacity (kW)	Refrigerant
1	Window AC	General Electric	AGM08FDM1	US	2.62	2.30	R-22
2	Mini-split	Haier	KFR-23W2012	China	3.402	2.36	R-22

Source: Authors' data from manufacturers

Figure 6: Two R-22 Units



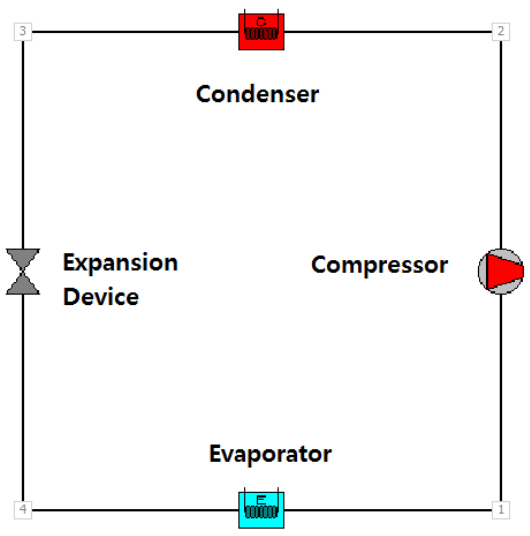


Top: Model#1, bottom: Model#2.

Source: Authors' pictures

VapCyc® is a vapor-compression cycle design and simulation tool. It is one the most popular air conditioner/heat pump (HP) modeling tools for industry. The tool is component based and can be populated with product data to characterize system performance. Figure 7 shows a typical vapor compression cycle with four key components: compressor, condenser, expansion device, and evaporator.

Figure 7: An Air Conditioner System Diagram in VapCyc®



Source: Authors' figure

Compressor Model

The compressor is the most important component of a refrigeration system. It behaves as the heart of the system, which compresses the refrigerant from a low-pressure gas to a high-pressure gas.

VapCyc® provides several compressor models. In this study, the compressor performance maps were given by manufacturers in the form of 10-coefficient polynomial equations defined by the AHRI Standards 540 (AHRI, 2015) as follows:

$$X = C_1 + C_2 t_S + C_3 t_D + C_4 {t_S}^2 + C_5 t_S t_D + C_6 {t_D}^2 + C_7 {t_S}^3 + C_8 {t_S}^2 t_D + C_9 t_S {t_D}^2 + C_{10} {t_D}^3$$

Where:

$C_1 \sim C_{10}$ = regression coefficients provided by the manufacturer

t_S = suction dew point temperature, [°F, °C]

t_D = discharge dew point temperature, [°F, °C]

X = Individual published rating, such as capacity [W, Btu/hr], input power [W,W] and refrigerant mass flow rate [kg/s, lbm/hr]

The 10 coefficients for mass flow rate and power consumption were derived from compressor maps as the inputs to model compressors. Standard R-22 compressors in the VapCyc® compressor library are selected and calibrated using the test data to reflect the energy performance of the actual compressors of Model #1 and #2.

Heat Exchanger Model

To have accurate simulation, CoilDesigner® software was used to model condenser and evaporator geometries and circuits. CoilDesigner® is a heat exchanger simulation tool for indoor and outdoor coil design. After the basic heat exchanger configuration is defined, circuit design, tube connection and airflow properties can be set up using the main graphical user interface (GUI) window (Figure 8). The heat exchanger generated by CoilDesigner® can be imported to VapCyc® as evaporator or condenser models for system design and optimization.

Figure 8: The Main GUI of CoilDesigner

The indoor and outdoor heat exchangers use copper tube coil with an aluminum fin design. The physical dimensions are measured from the product unit. Circuiting information is very important to get accurate simulation results. The coil circuitries are measured from the unit and then input into CoilDesigner®. Table 5 and Table 6 display the key input parameters of the window and mini-split AC models, respectively. The tube network diagrams show the detailed circuit configurations of the heat exchangers In both models, the evaporators and the condensers have two tube banks.

After the R-290 (drop-in) models are validated, system design optimizations are conducted to further improve the system efficiency and cooling capacity of Model #1 and Model #2.

Table 5: Key Heat Exchanger Input Parameters of the R-22 Window AC

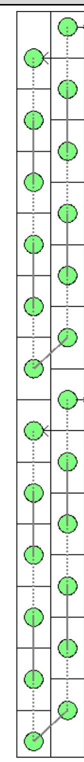
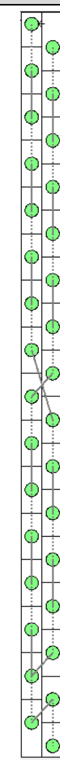
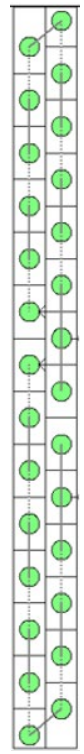
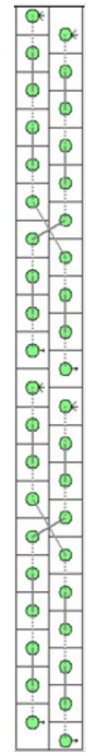
Input Parameters	Indoor unit		Outdoor unit	
Type	Fin-tube		Fin-tube	
Fin Type	Louver		Wavy-Herringbone	
Tube Length [m/in]	0.267/10.5		0.502/19.75	
Tube diameter [mm/in]	0.0099/0.39		0.0076/0.3	
Tube spacing vertical [mm/in]	0.035/1.389		0.028/1.1125	
Tube spacing horizontal [mm/in]	0.019/0.75		0.013/0.5	
Fin per inch	19		19	
Number of rows	2		2	
Number of circuits	2		2	

Table 6: Key Heat Exchanger Input Parameters of the R-22 Mini-Split AC

Input Parameters	Indoor unit		Outdoor unit	
Type	Fin-tube		Fin-tube	
Fin Type	Louver		Wavy	
Tube Length [m/in]	0.610/24		0.635/25	
Tube diameter [mm/in]	7.62/0.3		6.858/0.27	
Tube thickness [mm/in]	1.016/0.04		1.016/0.04	
Tube spacing vertical [mm/in]	0.022/0.85		0.022/0.85	
Tube spacing horizontal [mm/in]	0.013/0.5		0.019/0.75	
Fin per inch	20		16.5	
Number of rows	2		2.5	
Number of circuits	2		2	
Frontal flow area [m2/ft2]	0.163/1.75		0.274/2.95	

Testing Approach

Cooling capacity and energy efficiency testing for the six air conditioners analyzed were performed in order to determine the performance impacts of using R-290 as a refrigerant. Performance testing was conducted for two room air conditioners, two mini-split air conditioners, and two PTACs. The six air conditioners were tested with their existing refrigerant charge in accordance with United States Department of Energy (U.S. DOE) test procedures in order to establish each unit's baseline cooling capacity and energy efficiency. The existing refrigerant charge was then evacuated from each unit and "drop-in" testing using R-290 was performed. The drop-in testing consisted of determining the optimized R-290 charge level for each unit that maximized unit energy efficiency. Soft-optimization testing was then conducted on one of the room air conditioners to determine whether a simple hardware change (altering the length of the capillary tube) could further improve the overall performance of an air conditioner using R-290.

Test Facility and Test Procedures

Cooling capacity and energy efficiency testing were performed at Lawrence Berkeley National Laboratory's (LBNL's) HVAC and Refrigeration testing facilities, specifically the psychrometric test chamber (LBNL, 2021). LBNL's psychrometric test chamber's primary purpose is to evaluate the performance of central air conditioners and heat pumps with cooling capacities in the range of 6,000 to 90,000 British thermal units per hour (Btu/hr) (0.5 to 7.5 rated tons), and with heating capacities in the range of 6,000 to 60,000 Btu/hr (0.5 to 5-ton rated). It consists of side-by-side indoor and outdoor chambers with temperature, humidity, and airflow controlled independently. In addition, the psychrometric test chamber includes the necessary safety equipment for the testing of air conditioners utilizing flammable refrigerants such as R-290. The safety equipment includes refrigerant detection sensors and control equipment to shut down the operation of the test chamber in the event of a flammable refrigerant leak.

The two mini-split air conditioners were tested in accordance with the U.S. DOE's test procedure for central air conditioners and heat pumps, (U.S. CFR, 2021a) since mini-split air conditioners are regulated in the U.S. as central air conditioning systems. The U.S. DOE's central air conditioner and heat pump testing requires that the method of test use a psychrometric test chamber. The test procedure also requires that unit performance be evaluated under a number of indoor and outdoor test conditions. For single-speed systems, which is the design of the two mini-split air conditioners tested, the two primary test conditions are referred to as DOE "A" and DOE "B" test conditions. The DOE "A" test condition consists of indoor and outdoor temperatures of 80°F (degrees Fahrenheit) (26.67°C [degrees Celsius]) dry-bulb, 67°F (19.44°C) wet-bulb and 95°F (35°C) dry-bulb, respectively. The DOE "B" test condition consists of indoor and outdoor temperatures of 80°F (26.67°C) dry-bulb, 67°F (19.44°C) wet-bulb and 82°F (27.78°C) dry-bulb, respectively. Testing of the two mini-split air conditioners tested for this project was performed under DOE "A" and "B" test conditions.

The two window air conditioners and PTACs were also tested in LBNL's psychometric test chamber and in accordance with the method of test outlined in the U.S. DOE test procedure. Window air conditioners and PTACs are also required to be tested in accordance with the U.S. DOE's test procedures for window air conditioners (U.S. CFR, 2021b) and PTACs, (U.S. CFR, 2021c), which require the use of a calorimeter test chamber. Although LBNL's HVAC and Refrigeration testing facilities include a balanced ambient calorimeter test chamber, it is not retrofitted to test air conditioners with flammable refrigerants and, therefore, could not be safely used to conduct air conditioner testing for units charged with R-290. The primary drawback to using a psychrometric test chamber rather than a calorimeter for window air conditioner and PTAC testing is that the adverse performance impacts of indoor airflow recirculation, where a small portion of the discharged indoor airflow is drawn back into the air conditioner, cannot be captured. But because the effects of airflow recirculation are identical in air conditioners both with and without R-290, the relative performance impacts of R-290 are not affected. As specified in the U.S. DOE test procedures for window air conditioners and PTACs, the single test condition for unit performance is at the U.S. DOE "A" test condition, which consists of indoor and outdoor temperatures of 80°F (26.67°C) dry-bulb, 67°F (19.44°C) wet-bulb and 95°F (35°C) dry-bulb, respectively. Therefore, the two window air conditioners and two PTACs were evaluated only at the single U.S. DOE "A" test condition.

Air Conditioners Tested

Prior to the consideration of low-GWP refrigerants, all air-cooled air conditioners were designed to utilize refrigerant R-410A. For the U.S. air-conditioning market, almost all mini-split air conditioners, window air conditioners, and PTACs currently still use R-410A. Prior to R-410A, the predominant refrigerant used in air-cooled air conditioners was R-22. But R-22, which is a hydrochlorofluorocarbon, has been phased out of use in new air conditioning equipment since January 1, 2010, due to its ODP. Because R-410A has a higher volumetric capacity than R-22, the key components in an R-410A air conditioner, such as the compressor and heat exchanger coils, are designed differently and are not suitable for use in R-22 air conditioners. Because R-290 has very similar refrigerant characteristics to R-22, the components in an R-22 air conditioner are suitable for R-290. Therefore, to conduct drop-in R-290 testing, it necessitated acquisition of R-22 air conditioners for this project.

Equipment Cost Method

Cost of Equipment

The additional manufacture and installation costs of air conditioning equipment using R-290 as a refrigerant compared to R-410A were established by analyzing the manufacturer cost impacts of including safety components in an air conditioner that uses R-290, the manufacturing and process changes required to ensure that R-290 air conditioners are produced safely, additional costs for the compressor suitable for R-290, and changes required for the installation of air conditioners utilizing R-290. The approach for estimating the additional manufacturing and installation costs of AC equipment using R-290 compared to R-32 is described in Appendix C.

Manufacturer Cost Impacts

The safety standards in IEC 60079 (IEC, 2021) were used as a guide to identify the electrical components required for an air conditioner charged with an A3 refrigerant such as R-290. The safety standard requires that plastic fans instead of metal be utilized to ensure spark-resistance, direct current (DC) motors and solid-state components be used to ensure spark-resistance and the prevention of points of hot surface ignition, and the inclusion of additional components for refrigerant leak detection and controls to power down the air conditioner in the event of a refrigerant leak.

To establish the cost of the electrical components of an R-290 air conditioner, a purchased parts methodology was developed, which consisted of: (1) an existing parts analysis, which identifies the existing parts in an air conditioner, excluding the compressor that needs replacement to prevent potential sources of ignition if a refrigerant leak occurs; (2) additional cost for an R-290 compatible compressor; and (3) an additional parts analysis, which identifies the additional parts required to ensure that the air conditioner is powered down safely in the event of a refrigerant leak.

To conduct this existing parts analysis, a bill of materials (BOM) for a mini-split air conditioner and a window air conditioner were acquired to identify all of the purchased parts in typical air conditioning equipment. Supplier prices were then obtained for all of the purchased parts. Next, those existing parts requiring replacement to comply with the requirements in the IEC safety standards were identified. Supplier prices were then obtained for the parts replacing the non-compliant components. This analytical approach assumes that supplier prices provide a good estimate of the relative cost impact of a purchased part and, in turn, the relative cost increase of components required to ensure compliance with the IEC safety standards.

Because current air conditioners utilize R-410A as a refrigerant, their compressors and heat exchanger coils are not compatible with R-290. But the BOM existing parts analysis did not price and capture the conversion from R-410A to R-290 based components. As noted in the section *Testing Approach*, before R-410A became the most commonly used refrigerant in air-cooled AC designs, R-22 was the predominant industry-wide refrigerant. Because R-290 can be easily dropped into R-22 air conditioners and as will be noted in the section on *Testing Results*, even result in an efficiency benefit, the technologies required to produce R-290 based air conditioners would be almost the same as those previously needed for R-22 designs. As a result, it was assumed an industry conversion to produce R-290 air conditioners would be reverting back to well-known industry technologies and design practices that would require no significant research or development costs.

For the existing parts analysis, the BOM for a Fujitsu mini-split air conditioner (model ASU9RLF1 and AOU9RLFW1) (Fujitsu, 2021) and a Midea window air conditioner (model MWEUK18CRN1MCK8) (Midea, 2021) were obtained. Although only single models of a mini-split and window air conditioners were analyzed, it was assumed that the composition of the two air conditioner models were representative of current manufacturer design practices. In addition, even though a PTAC model was not analyzed, it was assumed design practices mirror those used in mini-split and window air conditioners. The existing parts analysis on the Fujitsu and Midea air conditioners revealed that all existing components complied with IEC safety standards: namely that all purchased parts are already plastic and all motors and control boards are already both direct current and solid state. Thus, in typical air conditioner designs, there are no cost impacts associated with replacing existing purchased parts to comply with IEC safety standards. For details on the existing parts analysis performed on the Fujitsu and Midea air conditioners, refer to Appendix B.

The existing parts analysis however did not include additional cost for an R-290-compatible compressor. The R-290 compressor design is more complex (for example, modifications to the assembly required for the coupling of temperature sensors). The incremental compressor cost is estimated by a United Nations Industrial Development Organization report to be $7.57 per unit (UNIDO, 2014) and that value is assumed here.

To conduct the additional parts analysis, additional parts for refrigerant leak detection and unit shut down were identified. As with the existing parts analysis, supplier prices were then obtained for the additional parts and were assumed to provide an estimate of the relative cost increase of components required to ensure compliance with IEC safety standards.

In order to ensure consumer safety, the components for a primary safety system were specified. The primary safety system consists of parts for refrigerant leak detection coupled with control logic in the primary control circuit board to shut down the unit when a leak is detected. In addition, solenoid shutoff valves are included to prevent refrigerant migration. Although a primary safety system based on leak detection is sufficient for ensuring consumer safety, the "additional parts analysis" went a step further and specified the components for a redundant safety system. The redundant safety system consists of pressure and temperature sensors coupled with a control logic in the primary control circuit board to monitor and assess the level of refrigerant charge. If deficient refrigerant charge levels are detected, then the control logic would shut down the unit and activate the solenoid valves. Table 7 shows the additional parts required for the primary and redundant systems in the Fujitsu mini-split air conditioner and the Midea window air conditioner. Note that no additional components are needed to incorporate the control logic into the primary control circuit board. It is assumed that leak and charge deficiency detection and unit control logic can be easily incorporated into current primary circuit board designs without a resulting purchase price impact. In other words, the research and development required to incorporate the safety detection and control logic are one-time investments that are not passed on to consumers in the form of higher purchase prices.

Due to the flammability of R-290, manufacturers need to ensure that their facilities are safe for producing air conditioners using an A3 refrigerant. Based on work performed for the Federal Republic of Germany by Becker (Becker et al., 2019) the following measures are required for the safe handling of R-290 in the production of mini-split air conditioners: (1) inclusion of gas sensors and alarms to detect refrigerant leaks, (2) ATEX-certified hardware in areas handling refrigerant, and (3) ventilation systems in areas handling refrigerant, and (4) refrigerant transfer lines.

Specific areas in the manufacturing facility where safety measures must be added include refrigerant storage, refrigerant charging systems, ultrasonic sealing of process tubing, leak detection after refrigerant charging, air conditioner performance test chamber and laboratory, and air conditioner repair.

There would be a capital investment to revert back to previous tooling equipment and to ensure that a production facility can handle R-290 with adequate safety equipment associated with handling flammability.

This cost impact has been estimated to be relatively minor since such investment costs are typically expensed and amortized over a time period equal to the useful life of the tooling equipment and annual depreciation expenses are spread across the total number of units. Colbourne (Colbourne et al., 2011) estimated this additional investment for converting from R-410A to R-290 at $300,000 and the cost per unit output to be less than $0.30 per unit (assuming 250,000 units produced annually), so this value was adopted.

Table 7: Primary and Redundant Safety System Components for R-290 Air Conditioners

Safety System	Fujitsu Mini-Split AC	Midea Window AC
Primary		
Refrigerant Leak Detection Sensors	Four (two each in indoor and outdoor units)	One
Solenoids	Two (one each in indoor and outdoor units)	Two
Redundant		
Thermocouple Wire	Four feet of wire	Two feet of wire
Pressure Transducers	Two (one each in indoor and outdoor units)	One

Source: Authors' assumptions

Notes on Reference Cases for Testing and Equipment Costs

As noted, the testing approach was to test R-290 compared to R-22 for R-290 drop in testing and soft optimization testing since R-290 refrigerant properties are fairly well matched to R-22 and the same compressor can be used, whereas dropping in R-290 in R-410A units is not possible due to mismatched components such as the compressor and heat exchangers. The baseline units were older and used R-22 units since the manufacture and installation of new R-22 AC or heat pump systems has been banned by the U.S. EPA since 2010. The research team also tried but was unable to obtain new R-22 units from abroad for refrigerant testing.

It should be noted, therefore, that the efficiency gains seen for R-290 (as will be discussed in the section on *Testing Results*) are relative to older AC units with R-22 and not necessarily to current or new AC units with R-410A. The magnitude of efficiency improvement in small ACs over the last decade is on the order of 10 percent, which is the same approximate magnitude of efficiency increase observed for R-290 units compared to R-22 in the used AC units. The starting assumption is that R-290 units have performance that is matching current R-410A units, but with some cost increase (described in the section *Equipment Cost Analysis Results*).

A recent simulation (Wan et al., 2021) shows that for 3-ton unitary air conditioners, R290 has the best performance compared to R-32, R-466A, R-452B, and R-410A. R-290 has about 12 percent higher coefficient of performance (COP) across the full temperature range and about 4 percent higher COP than R-32, where a constant isentropic and volumetric efficiency compressor model is used. Thus, as a sensitivity the team looked at the case where R-290 units have some cost increase but also improved performance (the case of R-290 having the same cost and performance of R-410A would have no net changes in either equipment or energy costs).

Also, as noted, base designs and components for small AC units with R-290 would be similar than the earlier generation of units with R-22. For example, the R-290 compressor would be very similar to R-22 compressors. To cost out the equipment costing for the R-290 units, R-410A units were used as a reference case since new equipment for these product types typically uses R-410A. The focus was primarily on any components that would need to be upgraded to spark-proof, and any new safety features such as additional sensors and pressure transducers that could incur additional cost, plus any increases in installation costs (applicable to mini splits where refrigerant is charged in the field).

LCC Analysis Approach

The metric used to evaluate the consumer economics of low-GWP equipment is the life-cycle cost (LCC). The LCC is defined as the total expense over the life of the system, including purchase, installation costs, and operating costs. The sum of the equipment purchase and installation costs is the total installed cost (TIC). Operating costs include maintenance, repair, and energy costs; these costs are calculated on an annual basis, then discounted to the present year and totaled to provide the total lifetime operating expense (LOX). The LCC is equal to the sum of these two components:

$$LCC = TIC + LOX$$

For each equipment type, the LCC is calculated for a sample of 10,000 consumers. For window AC and mini-split heat pumps, the consumers are commercial business owners, specifically hotels and motels. For each consumer, the annual operating hours, discount rate, and product lifetime are drawn from distributions. LCC results are presented for several scenarios:

- **Baseline:** The refrigerant is assumed to be the current market norm, the equipment price is estimated from data taken from a web search, and the product efficiency is equal to the U.S. DOE minimum.
- **R-410A to R-290:** Based on the cost analysis results described here, equipment prices increase by 3-7 percent. Efficiency is equal to the U.S. DOE minimum.
- **R-32 to R-290:** In this scenario the baseline refrigerant is assumed to be R-32. Manufacturer cost increases are assumed to increase by half as much as in the R-410A to R-290 case. Efficiency is equal to the U.S. DOE minimum.
- **Sensitivity Case - Efficiency:** This scenario assumes an increase of 10 percent in the product efficiency metric and calculates the resulting operating cost benefits. The product price is not affected. This scenario is used to provide insight into the value of efficiency for users of these products in California.
- **Sensitivity Case - Warmer Climate:** This scenario assumes an increase of 10 percent in cooling season operating hours, and a decrease of 10 percent to heating season operating hours. It is included to provide insight into the potential energy and cost impacts of changing climate patterns.

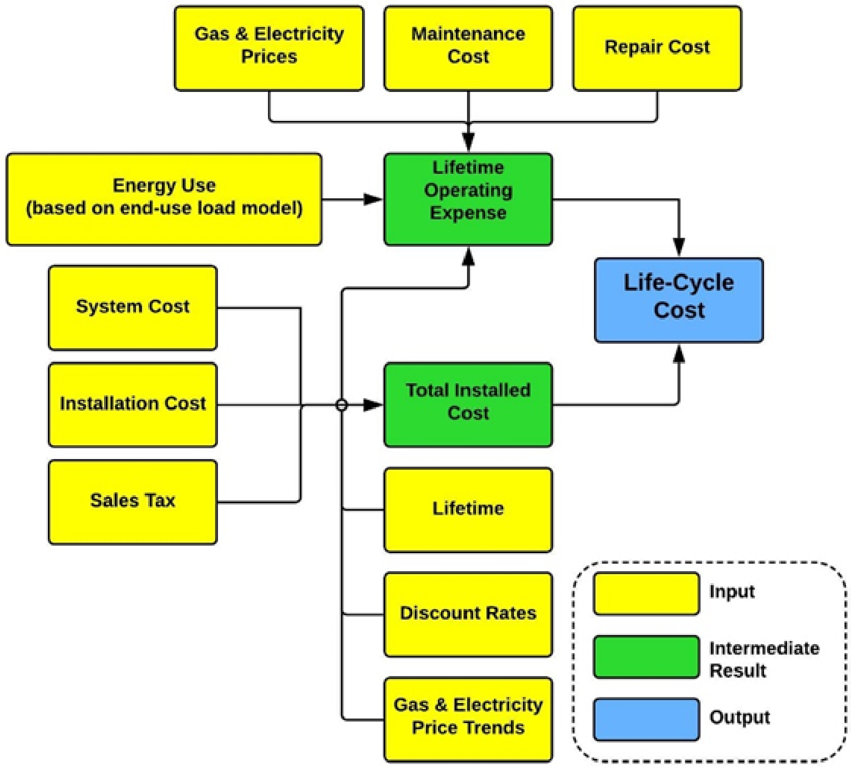
This report does not attempt to construct a cost-efficiency relationship for R-290 AC products. In general, even if the industry were to shift to widespread use of R-290 as a refrigerant, product efficiency would still be regulated by federal standards. Hence, there would be no efficiency increase automatically induced by a change of refrigerant, and it is assumed that manufacturers would continue to offer the same range of products. The LCC scenarios presented here are used to illustrate the relative contributions of purchase and operating costs to the overall cost of ownership, and to quantify the consumer impacts of increased product prices and efficiency.

LCC Inputs

This section itemizes the data sources and values used for the LCC inputs. A more detailed discussion of how operating hour distributions were determined is presented in the next section.

Figure 9 presents a general schematic of how the calculation proceeds for one member of the sample. The yellow boxes represent data inputs, the green boxes intermediate results, and the blue box the LCC output.

Figure 9: Schematic of the Life-Cycle Cost Calculation



Source: Authors' figure

1. **Product Prices:** Product prices are based on baseline prices for the four product types meeting minimum energy efficiency drawn from federal energy efficiency standards technical support documents for PTAC/PTHP and room AC, and from online product prices and a Building Services Research and Information Association (BSRIA) report for mini split heat pumps (BSRIA Inc., 2018).

2. **Electricity Prices:** these were estimated based on data published in 2019 using the methods described in Coughlin (Coughlin and Beraki, 2018; 2019). The analysis uses seasonal marginal and average prices, for the commercial and residential sectors. The summer prices are applied for energy use during the months May through September, and winter prices to the rest of the year. Average prices are used to estimate the energy operating cost in the base case (no efficiency change), and marginal prices are used to value energy savings in the higher-efficiency case.

3. **Repair and Maintenance Costs:** there is no evidence to suggest that repair and maintenance costs would change due to a change of refrigerant, so these costs are assumed to be the same in all scenarios. Because they are unaffected by the choice of scenario, these costs were not included in the analysis.

4. **Energy Use:** cooling energy use for each product type is estimated based on the product energy efficiency ratio (EER). The EER is defined as the ratio of the heat removed to the power consumed. As described in the next section, building simulations were used to construct distributions of annual operating hours for each equipment type.

Over one year, the total heat removed is equal to the equipment capacity times the annual operating hours, and the energy use is obtained by dividing by the EER. A similar approach is used to estimate heating energy use; for heating the equipment COP is used instead of the EER.

5. **Installation Cost:** these are assumed not to vary with LCC scenario; hence, these costs are not included in this analysis.
6. **Lifetime:** equipment lifetimes are defined as the length of time the unit is in operation before being replaced. These are represented using a Weibull distribution. The distribution parameters for window AC and for PTACS were based on analyses published by DOE. For MSHP (mini-split heat pump), the lifetime distributions were assumed to be equal to those calculated by U.S. DOE for the central air conditioner rulemaking (U.S. DOE, 2016). The average lifetimes are eight years for PTAC/PTHP, 10 years for window AC, and 13 years for MSHP.
7. **Discount Rates:** these represent the rate at which future expenditures are discounted, typically estimated using the purchaser's cost of capital. The discount rate is applied in the LCC to future year energy cost savings. Distributions of discount rates for the residential sector were adopted from data published for the U.S. DOE window AC rule (U.S. DOE, 2016), and for the commercial sector from the CUAC rule (U.S. DOE, 2015). The average discount rate for the residential sector is 4.3 percent and for the commercial sector is 5.1 percent.
8. **Electricity Price Trends:** electricity prices were assumed to grow over the lifetime of the product. The annual growth rate was estimated as 3 percent, based on growth trends for California over the last 20 years.

Operating Hour Distributions

For each product type, annual operating hours are represented as distributions. Although the product testing and performance modeling considered only the cooling side for AC units, the consumer LCC considers AC and HP products. The mini-split market is dominated by mini-split HPs, so only these units are modeled in the LCC. Shipments of packaged terminal units are split fairly evenly between HP and AC, so both types of units are modeled. For PTAC/HP and MSHP, distributions are constructed for a total of four categories: summer cooling, summer heating, winter cooling and winter heating. For room air conditioners (RACs), only summer cooling is considered. Each product type has a different data source for the operating hour distributions.

Operating hours for window AC were estimated from the 2009 Residential Energy Consumption Survey (RECS) (U.S. EIA, 2009). While 2009 is not the most recent survey, it is the only RECS data set that allows California to be separated out from the Pacific census division. The RECS data includes a flag for cooling technology type, a categorical variable for the age of a window/wall unit, number of individual ACs in the residence, the annual cooling kilowatt-hours (kWh), and a sample weight for the row. Only RECS sample rows with cooling types equal to window/wall units were used in the analysis. To estimate annual cooling hours, the age data were converted to an estimate of the EER for the unit, based on data analyzed for the U.S. DOE window AC rulemaking (U.S. DOE, 2020b). Annual operating hours were estimated as:

$$OP\_hour = Annual\_kWh * EER/(Capacity)$$

Where:

The capacity is set equal to the value for the representative unit, 8,000 Btu/hr. To construct a distribution, operating hours for each RECS sample row are assigned to a bin. Bins are labelled n, with the bin limits equal to [n*200, (n+1)*200]. The total sample weight for each bin is calculated by adding up the RECS weight for each row assigned to the bin and normalizing to 100 percent for all included rows. Finally, the average value of the operating hours within each bin is used as the representative value for that bin.

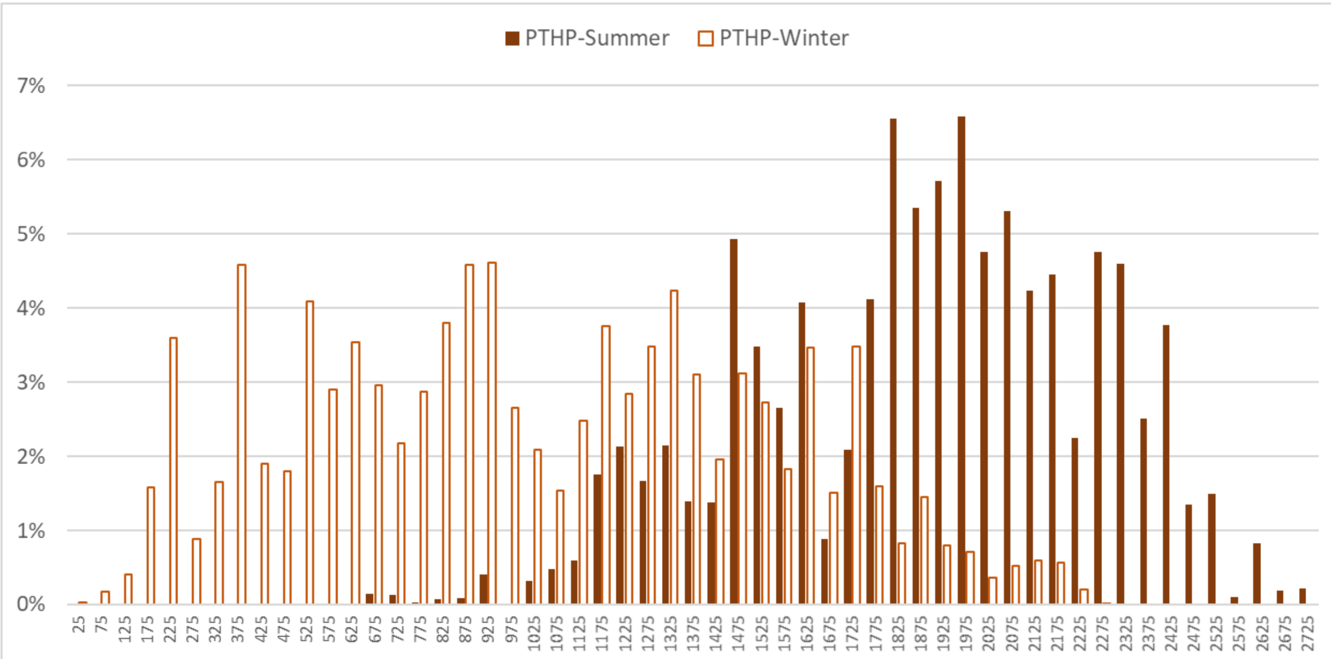
A similar approach is used to calculate operating hour distributions for MSHP and PTAC/HP. For these products, information about product use is taken from building simulations performed using EnergyPlus and the U.S. DOE Commercial Reference Buildings (U.S. DOE, 2021), for the New (2004) vintage. The small-hotel prototype (which models 24 individual systems) was used to generate operating profiles for PTACs, and the mid-rise apartment (which models 35 individual systems) was used for the MSHPs. The simulations provide hourly profiles for one year, for each of the 16 California climate zones defined for Title 24 (EPS, 2021) based on Typical Meteorological Year weather data (NREL, 2021). The results are processed as follows:

1. For each location and system:
    a. The hourly energy use is aggregated into four categories: summer cooling, summer heating, winter cooling and winter heating. Summer is defined as May through October.
    b. As with window AC, the seasonal end-use operating hours are assigned to bins; in this case the bins are of width 50.
    c. The system capacity is estimated as the maximum cooling rate times a scaling factor of 1.2; the scaling factor adds 20 percent to account for the difference between the maximum load under median weather and the design-day load.
    d. A unit weight is estimated as the ratio of the system capacity to the representative capacity for that equipment type.
2. For each location, a climate zone weight is derived based on population within that zone. The climate zone weight and unit weight are multiplied together to define a total weight for each system in each location.
3. From those steps, each location and system has been assigned a weight and a bin for the operating hours, by both season and end use. For each bin, the total weight is added up over all the systems and locations. The result provides a distribution represented as a weight for each bin, and a representative value of the operating hours within each bin. The latter is calculated as the average over all rows assigned to that bin.

The results of this calculation are illustrated in Figure 10, which shows the bin weight on the vertical axis and the bin average operating hours as a label on the horizontal axis, for PTHPs.

The distribution is broad, indicating a wide range of levels of use across different California climate zones. Summer use (primarily for cooling) is significantly higher than winter use.

Figure 10: Annual Operating Hour Distribution for PTHP



The horizontal axis labels provide the average annual operating hours for that bin, and the vertical axis is the relative weight for the bin.

Source: Authors' calculation

Approach to Model California Impact Analysis

Modeling the Shipments of PTAC, PTHP, Window AC, and Mini-Splits

The purpose of the shipments model is to provide an estimate of the number of PTACs, PTHPs, window ACs, and mini-splits that will be installed in California in each year of the analysis periods 2022 to 2051 and 2023/2025 to 2052/2054. The reference shipments model is composed of installation into new construction and replacements of existing units. There is also a high shipments case for window ACs and mini-splits: for Window ACs, the high case assumes all homes without AC in the hot-dry and mixed dry regions of California will buy a window AC over the 30-year analysis period, for mini-splits, the high case assumed that mini-splits take over the market for small gas furnaces in multi-family and mobile homes. (Note: all results shown use the reference model unless explicitly noted that the high-case was used). The high case is only modeled for the (2023/2025 to 2052/2054) analysis period.

Modeling the Energy, Emissions, and Refrigerant Savings

The shipments over the 30-year period are used to calculate the amount of refrigerant emissions (in CO_2e) that would be avoided if all PTACs/PTHPs, window ACs, and mini-splits in California were to switch from R-410A or R-32 to R-290. Two scenarios were modeled: the first assumes a switch from R-410A/R-32 to R-290, with no corresponding change in energy efficiency, the second scenario assumes a switch from R-410A/R-32 to R-290 and a corresponding 10 percent increase in energy efficiency. In the first scenario, the only benefits are from avoided refrigerant emissions, which are reported in terms of CO_2e. In the second scenario, environmental benefits from reduced energy use along with economic benefits from lifecycle cost savings are included with the benefits from reduced refrigerant emissions. Additional analyses to switch from R-410A to R-32 can be found in Appendix C.

Model Structure and Input Data

PTACs/PTHPs

Three data sources were used to estimate the shipments of PTACs and PTHPs: national sales data from 2014-2021 from BRG Building Reports (BRG Building Solutions, 2020), population data from the United States Census Bureau (U.S. Census Bureau, 2021), and the Annual Energy Outlook (AEO) 2021 Commercial Floorspace Projections (U.S. EIA, 2021).

The BRG national sales data was scaled to the California level using population data from the U.S. Census. The AEO provides projections of new and existing commercial floorspace through 2050, by census division. State population data was used to estimate the portion of floorspace within Census Division 9 in California. Next, the existing stock of PTAC/PTHPs in 2021 was calculated by taking the sum of the shipments over the average lifetime of a PTAC/PTHP, which is eight years. To calculate the amount of reduced shipments (due to lost floorspace) and new shipments (due to new construction), the average square footage per PTAC/PTHP was calculated by dividing the total lodging floorspace in 2021 by the PTAC/PTHP stock in 2021. The average square footage per PTAC/PTHP is equal to 1,495 square feet.[6]

The future shipments are equal to the shipments from eight years prior (the length of an average PTAC/PTHP lifetime), minus the reduction of shipments from lost floorspace (lost floorspace divided by 1,495), plus new shipments from the floorspace added in a year (new floorspace divided by 1,495). The market was assumed to be 55 percent PTACs and 45 percent PTHPs based on market share data from the 2015 final rule for PTACs and PTHPs (U.S. DOE, 2015).

Window AC

The U.S. DOE published a notice of proposed rulemaking for consumer room air conditioners (window AC) in June 2020 (U.S. DOE, 2020b). The National Impact Analysis section of this rulemaking contains national shipment projections through 2051 (U.S. DOE, 2016). Historical shipments for California from 2000 to 2014 were used to estimate the percentage of national window AC shipments that would go to California. The 14-year average proportion of California shipments to national shipments was applied to the national shipments' projections of room air conditioners in the national impact analysis of the 2020 Notice of Proposed Rulemaking. A high shipments case was also developed to account for homes that do not have AC but will adopt it in the future due to a warmer climate. In this case, all homes in the mixed-dry and hot-dry regions of California that currently do not have a window AC would acquire one over the course of the analysis period.

[6] This average includes all floorspace in lodging facilities, not only the floorspace that is conditioned by PTAC/PTHPs.

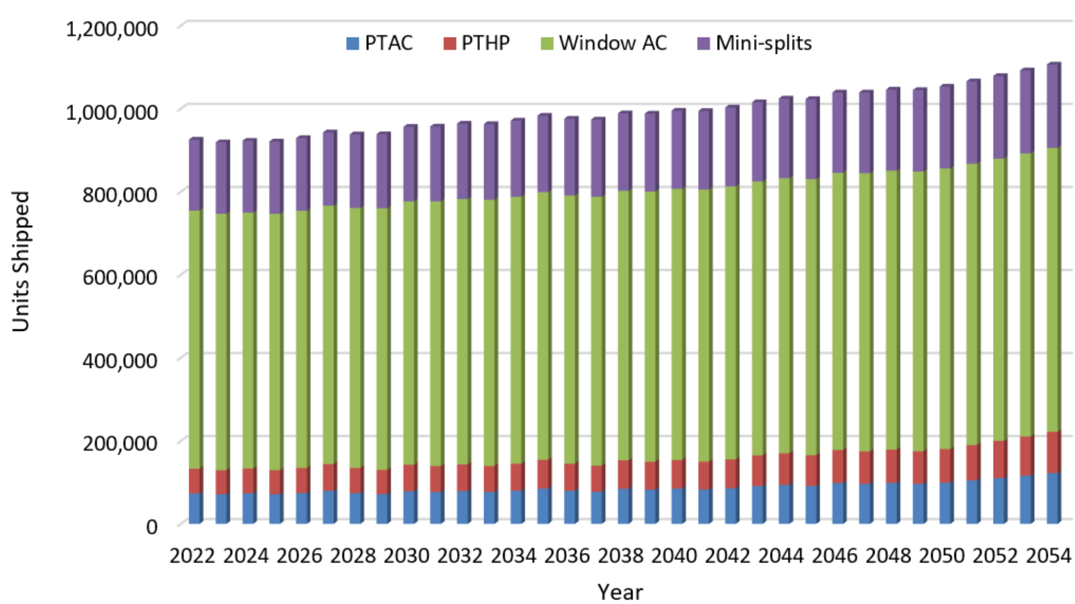
Mini-Splits

A BSRIA report on VRF and mini-splits from 2018 provided national shipment estimates of mini-splits for 2016, 2017, and 2018. (BSRIA Inc., 2018) Census data was used to estimate the proportion of national shipments that would go to California (based on population). To estimate shipments in 2022, the team used a 12-percent growth rate (which is the rate of growth from the actual shipments data from 2016 to 2018). After 2022, new shipments are estimated by calculating the percentage increase in new homes (single family, multifamily, and mobile homes) and applying that growth rate to the previous year of shipments. A high shipments case was also developed; in this case furnaces used in multifamily and mobile homes switch to mini-split heat pumps over the course of the analysis period.

Total Capacity Shipped

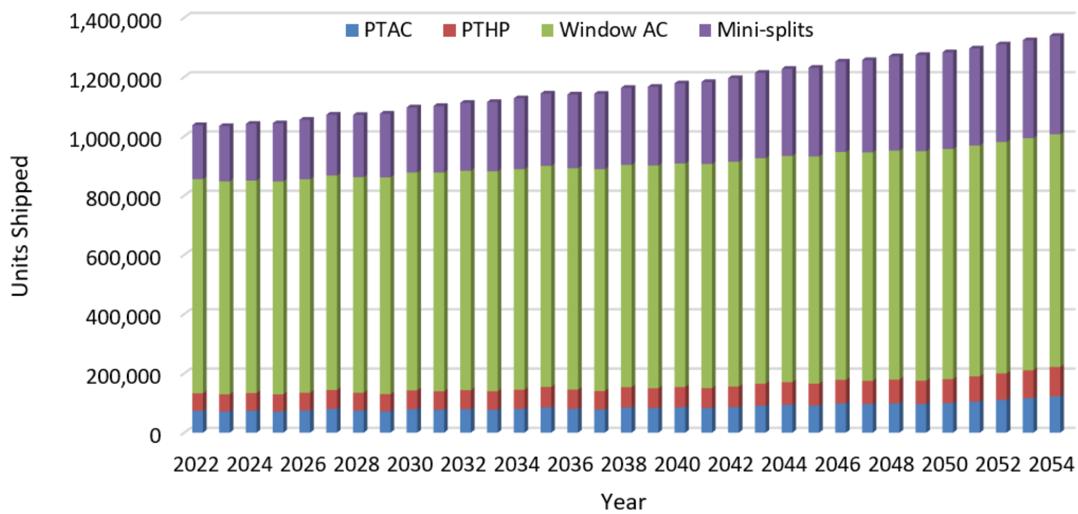
Three representative capacities are used in the model: PTACs/PTHPs (9,000 Btu/hr), window AC (8,000 Btu/hr), and MSHP (18,000 Btu/hr). To properly estimate the impact of a different refrigerant or higher efficiency piece of equipment, the shipments multiplied by the representative capacity must equal the total capacity shipped. Market share data by cooling capacity was gathered for each product and the weighted average cooling capacity was calculated for each product, then multiplied by the annual shipments. This total capacity shipped was then divided by the representative capacity so that the shipments account for the distribution of cooling capacities on the market. Figure 11 and Figure 12 display the reference and high case shipments projections.

Figure 11: Reference Case Shipment Projections



Source: Author calculation

Figure 12: High-Case Shipment Projections



Source: Author calculation

CHAPTER 3: Project Results

Modeling Results

This section describes the simulation results of a window air conditioner unit and a mini-split unit (Table 8).

Table 8: Fixed-Speed AC Models

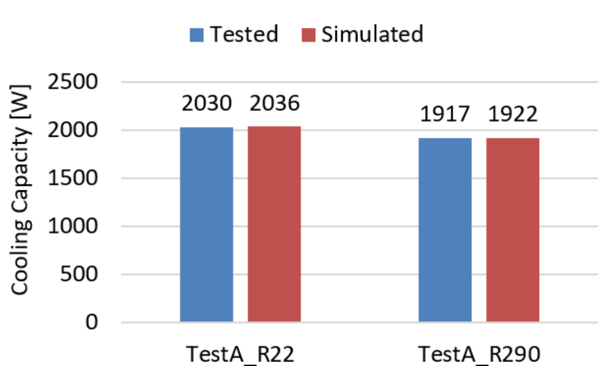
Model #	Product Type	Brand Name	Model Information	Market	Nameplate EER (W/W)	Nameplate Cooling Capacity (kW)	Refrigerant
1	Window AC	General Electric	AGM08FDM1	US	2.62	2.30	R-22
2	Mini-split	Haier	KFR-23W2012	China	3.402	2.36	R-22

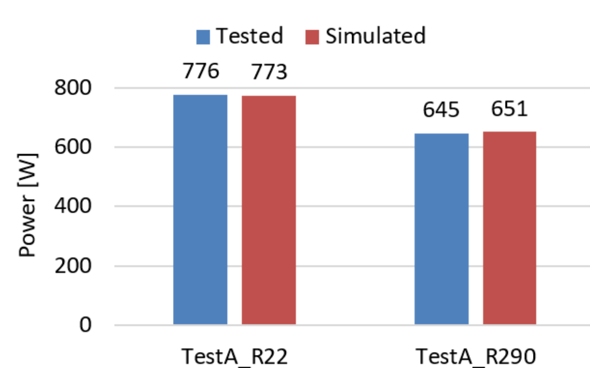
* Model number corresponds to the R-22 outdoor condensing unit.

Source: Authors' data from manufacturers

The selected AC units were tested in LBNL's psychrometric test chamber by following the AHRI 210/240 testing procedure described in the Testing section of Chapter 2. VapCyc® and CoilDesigner® were used to develop physics-based models for detailed energy performance simulations, as described in Chapter 2. The test and simulation results of using R-22 and R-290 (drop-in) refrigerants are shown in Figure 13 and Figure 14 for comparison. It can be observed that Model #1 and Model #2 simulations show good agreement with the test data. The differences between tests and simulations are within ±5 percent. A simple R-290 refrigerant drop-in gives a 13.5 percent and an 8.6 percent higher energy efficiency rating (rated EER) compared to the original R-22 window and min-split unit, respectively. However, decreases in cooling capacity of 12.4 percent and a 16.8 percent were observed due to the refrigerant change.

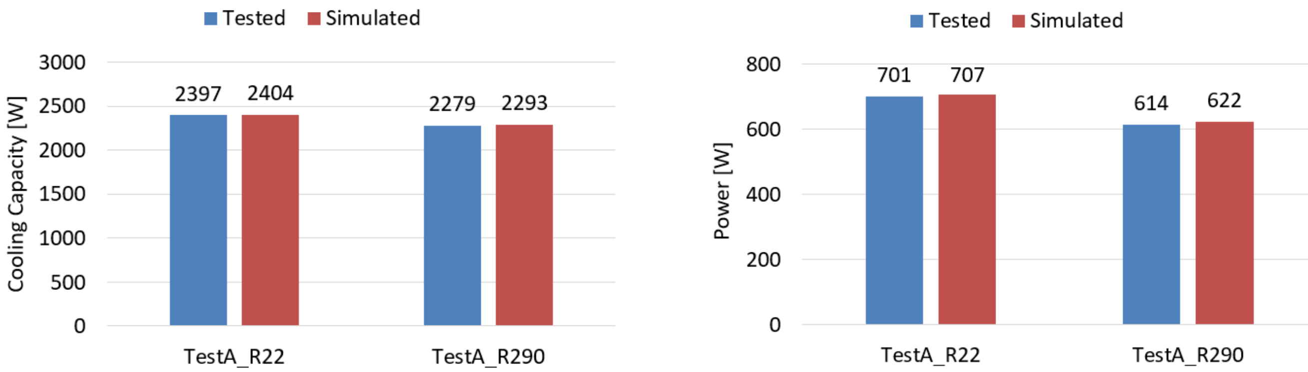
Figure 13: Model Calibration of the Window AC Under AHRI Test A Conditions





Source: Author testing and simulation

Figure 14: Model Calibration of the Mini-Split AC Under AHRI Test A Conditions



Source: Author testing and simulation

Optimization Analysis

After the R-290 (drop-in) simulation models are validated, system design optimizations are conducted to further improve the system efficiency and cooling capacity of Model #1 and Model #2. The objective is to find the best design option of the AC units using low-GWP R-290 refrigerant with minimum design changes. A genetic algorithm is applied to maximize the system EER. Genetic algorithm is a search algorithm inspired by natural selection; is widely used in engineering applications to provide high quality optimized designs. The independent variables to be optimized are represented using "genes" in a string (chromosome). There are three basic operators including mutation, crossover, and selection. Each optimization analysis considers 1100 design options and returns the optimal design.

Fan efficiency improvement can decrease power demand from the fan motors and improve overall system efficiency. The baselines in Models #1 and #2 use alternating current fan motors. Switching to high-efficient direct current (DC) fan motors can easily save 20 percent to 30 percent fan energy consumption (Goetzler et al., 2013). In this report, it is assumed 20 percent power saving potentials for evaporator and condenser fans.

Table 9 and Table 10 show key optimization constraints and the optimal design scenarios of the window AC and mini-split AC, respectively. Appendix A summarizes the detailed design changes. Figures 15 and 16 show the system energy performance of the optimized AC units. The optimal window AC design achieves 6.8 percent power consumption decrease and a 3.5 percent cooling capacity increase when compared to the R-290 drop-in, resulting in 11.1 percent system EER improvement. This translates to a 24.1 percent EER improvement from the original R-22 baseline. Similarly, the optimal mini-split AC design achieves a 2.2 percent power consumption decrease and a 4.5 percent cooling capacity increase compared to the R-290 drop-in, which gives a 6.9 percent system EER improvement. This translates to a 15.8 percent EER improvement from the original R-22 baseline. From sensitivity analysis of the 2200 optimization design options of Model #1 and #2, using longer condenser tube length is the most promising design option for AC system energy-efficiency improvements.

It should be noted that, to demonstrate how simulations can help speed up the process for new AC system design, the optimal design options discussed in this research only reflect the optimization results based on the 12 key design variables listed in Table 9. If different design variables are used, the optimization results will change. Furthermore, all the design variables are assumed to be independent. Further analysis needs to be conducted if certain variables are dependent upon each other for system efficiency.

Table 9: Summary of System Design Optimization for Model #1

Component	Property	Baseline	Lower Bound	Upper Bound	Model #1 Optimal Design
System	Subcooling [K]	6.34	2	10	5.42
System	Superheat [K]	3.47	3	15	3.00
Evaporator	Tube length[m]	0.2667	0.21	0.32	0.32
Evaporator	FPI	19	15	23	22
Evaporator	Vertical spacing	0.035281	0.028	0.042	0.028
Evaporator	Horizontal spacing	0.01905	0.015	0.023	0.015
Condenser	Tube length[m]	0.50165	0.4	0.61	0.55
Condenser	FPI	19	15	23	21.5
Condenser	Vertical spacing	0.028258	0.21	0.034	0.024
Condenser	Horizontal spacing	0.0127	15	0.015	0.014

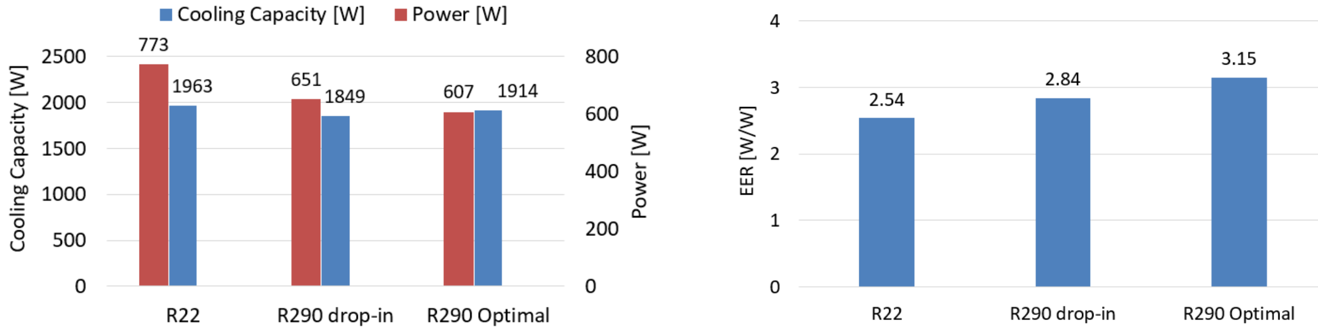
Source: Author simulation

Table 10: Summary of System Design Optimization for Model #2

Component	Property	Baseline	Lower Bound	Upper Bound	Model #2 Optimal Design
System	Subcooling [K]	6.34	2	10	7.2
System	Superheat [K]	3.47	3	15	3.28
Evaporator	Tube length[m]	0.63	0.5	0.75	0.6
Evaporator	FPI	18	14.4	21.6	21.4
Evaporator	Vertical spacing	0.022	0.018	0.027	0.027
Evaporator	Horizontal spacing	0.013	0.01	0.015	0.011
Condenser	Tube length[m]	0.737	0.59	0.88	0.86
Condenser	FPI	18.5	14.5	22.5	22.5
Condenser	Vertical spacing	0.025	0.02	0.03	0.024
Condenser	Horizontal spacing	0.022	0.017	0.027	0.017

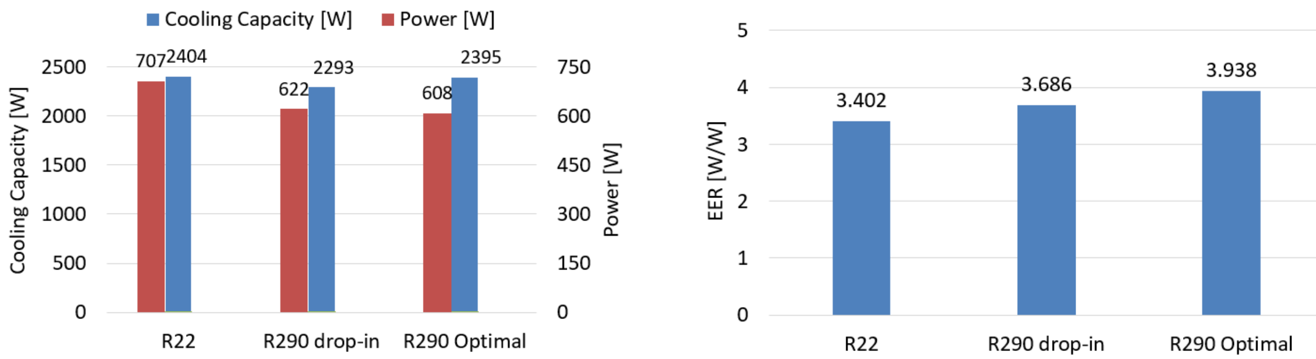
Source: Author simulation

Figure 15: Optimal Design of the R-290 Window Unit



Source: Author simulation

Figure 16: Optimal Design of the R-290 Mini-Split Unit



Source: Authors' simulation

Testing Results

Table 11 lists the R-22 air conditioners acquired for testing. Note that for the General Electric mini-split air conditioner an R-22 indoor unit was unavailable; an R-410A indoor unit was therefore paired with the R-22 outdoor condensing unit. Brand name, model number, cooling capacity, EER, and R-22 charge level are listed in the table. The cooling capacity and the EER at the U.S. DOE "A" test condition (outdoor temperature of 95°F [35°C]) were established through testing at LBNL's psychrometric test chamber.

Table 11: Air Conditioners Testing Results

Type	Brand Name	Model No.	Cooling Capacity (Btu/hr)	EER @ 95°F (Btu/hr/W)	R-22 Charge (kg)
Window AC	General Electric	AGM08FDM1	6,927	8.9	0.47
Window AC	Midea	Prototype	7,112	8.3	0.32
Mini-Split AC	Haier	KFR-23W2012	8,181	11.7	1.00
Mini-Split AC	General Electric	GESFBH24OUAA*	22,074	8.7	2.15

Type	Brand Name	Model No.	Cooling Capacity (Btu/hr)	EER @ 95°F (Btu/hr/W)	R-22 Charge (kg)
PTAC	Trane	PTED0702GCA	6,199	9.7	0.65
PTAC	General Electric	AZ38H15DADM1	9,956	6.5	0.85

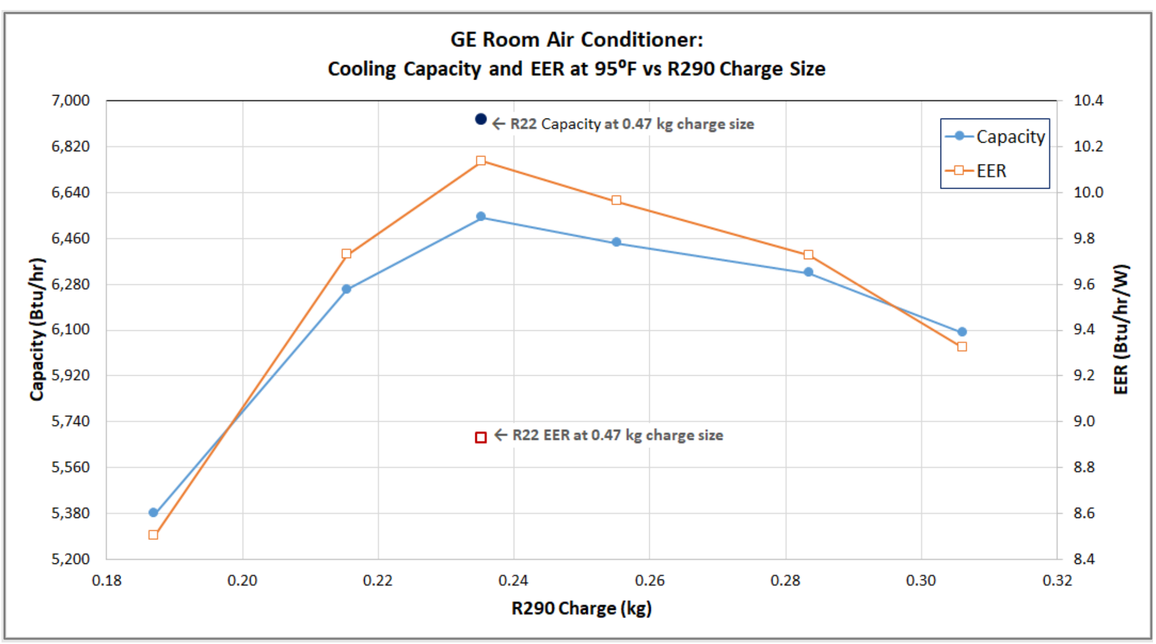
* Model number corresponds to the R-22 outdoor condensing unit. Due to the unavailability of an R-22 indoor unit, an R-410A indoor unit was used.

Source: Author testing

R-290 Charge Optimization

For each of the six air conditioners listed in Table 11, R-290 drop-in testing was performed to determine optimized R-290 charge levels. Optimization was determined solely at the U.S. DOE "A" test condition (outdoor temperature of 95°F (35°C) by testing each air conditioner over a wide range of R-290 charge levels. Based on research conducted at Oak Ridge National Laboratory (ORNL), the optimized R-290 charge level was expected to be approximately 50 percent of the baseline R-22 charge level (Abdelaziz et al., 2015). Figure 17 shows the R-290 testing results for the General Electric window air conditioner. As shown, drop-in testing was performed spanning a range of R-290 charge levels that were 40 percent to 65 percent of the R-22 baseline level. As indicated, the optimum R-290 charge level that maximized energy efficiency was 0.235 kilograms (kg) or 50 percent of the R-22 baseline level. The cooling capacity was also maximized at the optimum R-290 charge level. Appendix B provides figures similar to Figure 17 for the six air conditioners that went through R-290 charge optimized testing.

Figure 17: R-290 Charge Optimization Test Results for the General Electric Window Air Conditioner



Source: Author testing

Table 12 summarizes charge optimization test results for each of the six air conditioners tested. Table 12 shows the optimum R-290 charge level, the cooling capacity, unit power, and EER at the optimum R-290 charge level, as well as the performance impacts of the optimum R-290 charge level relative to the R-22 baseline performance. With the exception of the General Electric mini-split air conditioner, optimized R-290 charge levels either equaled or were close to 50 percent of the R-22 baseline level. Because the General Electric mini-split air conditioner consisted of an R-22 outdoor condensing unit and an R-410A indoor unit, the R-290 optimized charge level was far below the R-22 baseline level. For all six air conditioners tested, the optimized R-290 charge level increased the energy efficiency substantially without significantly impacting the cooling capacity of the air conditioner. In the case of the General Electric PTAC, cooling capacity even increased at the optimum R-290 charge level. Across the six air conditioners tested, the average energy efficiency increase was over 13 percent and the average cooling capacity decrease was 1 percent. If the surprisingly high cooling capacity increase of the General Electric PTAC is disregarded, the average cooling capacity decrease is 4 percent.

Table 12: R-290 Charge Optimization Test Results

Type	Brand Name	Optimum R-290 Charge		Unit Performance at DOE "A" Test Condition with R-290			Percent Impact relative to R-22		
		Charge (kg)	**Percent of R-22**	**Cooling Capacity** (Btu/hr)	**Power** (W)	**EER** (Btu/hr/W)	**Cooling Capacity**	**Power**	**EER**
Window AC	GE	0.24	50%	6,542	645	10.1	-6%	-17%	+14%
Window AC	Midea	0.16	50%	6,901	753	9.2	-3%	-12%	+10%
Mini-Split	Haier	0.50	50%	7,779	614	12.7	-5%	-12%	+9%
Mini-Split	GE	0.65	30%*	21,606	2,128	10.2	-2%	-16%	+16%
PTAC	Trane	0.36	55%	6,207	570	10.9	0%	-11%	+12%
PTAC	GE	0.51	60%	10,937	1,389	7.9	+10%	-9%	+21%

* Optimized R-290 charge level was significantly below 50 percent of R-22 baseline level due to mini-split consisting of an R-22 outdoor condensing unit and an R-410A indoor unit.

Source: Author testing

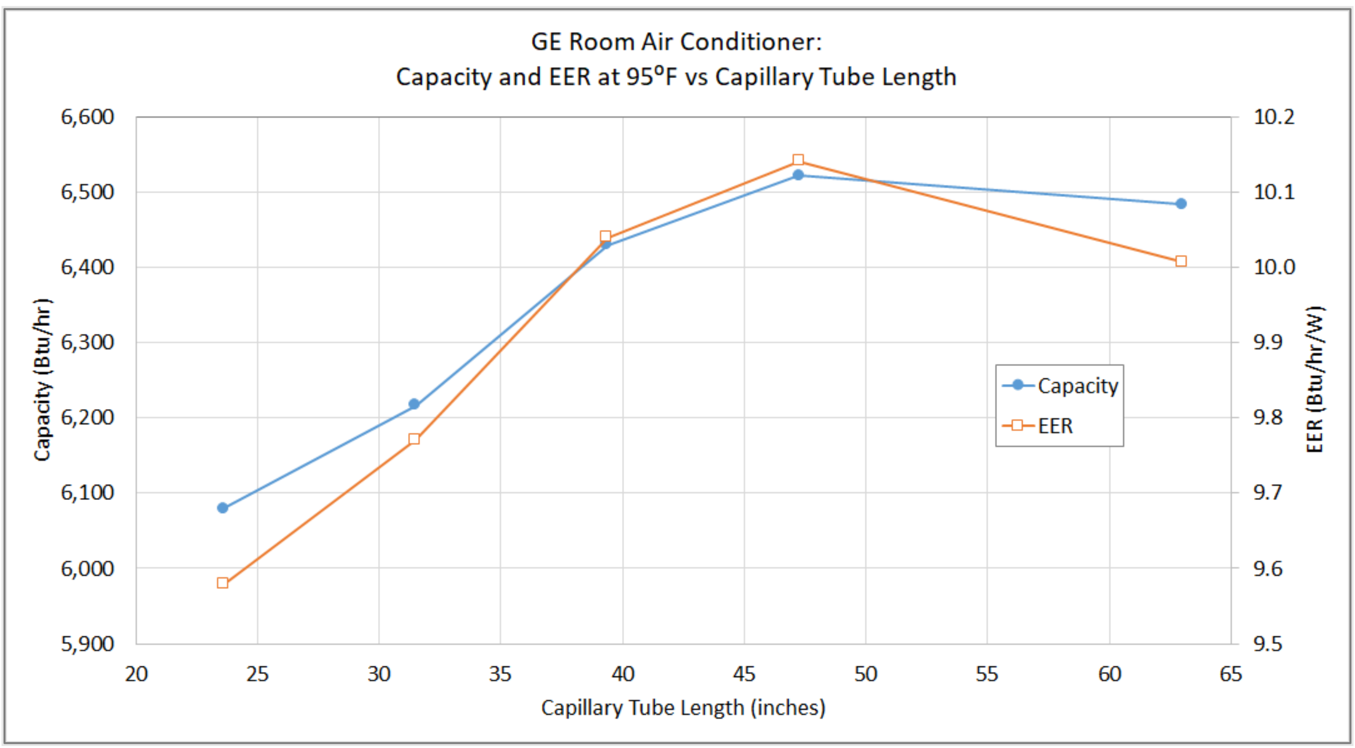
R-290 Soft Optimization

To determine whether further energy efficiency gains could be achieved from R-290, soft optimization of the General Electric window air conditioner was performed. Soft optimization consists of only minor hardware changes to the air conditioning equipment, specifically no replacement of the compressor and no alterations to the heat exchanger coils. The soft optimization conducted on the General Electric window air conditioner consisted solely of altering the length of the capillary tube, which is the flow control device that regulates refrigerant flow from the condenser to the evaporator. From research conducted at ORNL, increasing the length of the capillary tube is expected to increase cooling capacity but negatively impact energy efficiency (Abdelaziz et al., 2015). In other words, soft optimization is expected to recapture the cooling capacity loss due to R-290 charge optimization while having a negative impact on energy efficiency.

An experimental apparatus was designed and implemented in order to test the window air conditioner with multiple capillary tube lengths. The experimental setup required additional refrigerant tubing in order to route the refrigerant flow through the apparatus. Thus, 0.04 kg of R-290 was added to the optimum charge level of 0.235 kg for the General Electric window air conditioner. The result of the added R-290 charge and the experimental apparatus lowered the cooling capacity from 6,542 Btu/hr to 6,080 Btu/hr, and the energy efficiency from 10.1 EER to 9.58 EER. Thus, the impacts of soft optimization were evaluated relative to the adjusted optimized cooling capacity and energy efficiency values.

Figure 18 shows the results of soft-optimization testing. Varying lengths of capillary tube were evaluated ranging from the initial length of 23.6 inches to a maximum length of 63 inches. The resulting optimum capillary tube length was 47.25 inches, which resulted in relative cooling capacity and EER increases of 7 percent and 6 percent, respectively. Although it was expected that cooling capacity would increase from soft optimization, it was surprising that energy efficiency also increased. More comprehensive testing on additional air conditioners is needed to verify the previous results.

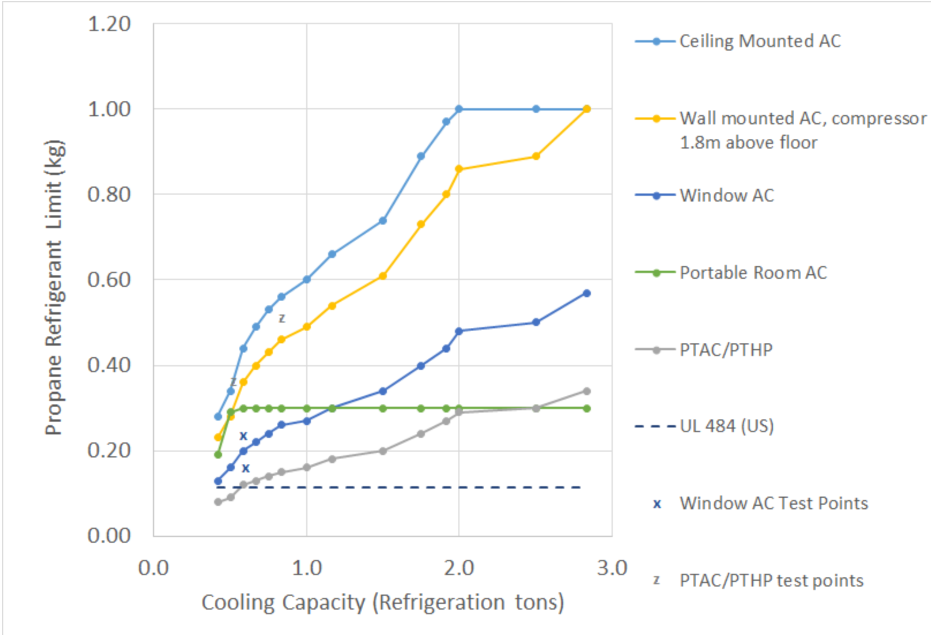
Figure 18: R-290 Soft Optimization Test Results for the General Electric Window Air Conditioner



Source: Author testing

Figure 19 shows the U.S. EPA 2015 and UL 484 charge limits and the window AC and PTAC test points for R-290 from this study. The two PTAC test points are much higher than the current charge limit regulations, while the window AC shows that the average of the two tested units have a propane refrigerant charge that meets the U.S. EPA charge limit.

Figure 19: R-290 Test Data Compared to U.S. EPA Charge Limits and UL 484 Charge Limits



Source: U.S. EPA 2015, UL 2019, and author testing

Test Summary

The charge optimization and soft-optimization conducted with R-290 demonstrates that cooling capacity and energy efficiency gains can be achieved relative to R-22 air conditioner designs. Although testing indicates that cooling capacity and efficiency gains can be substantial (relative to R-22 designs); the current air-conditioning market is dominated by R-410A designs that are not compatible with R-290, so there is the question of whether R-290 air conditioners would be more efficient than R-410A designs. As noted, a recent simulation (Wan et al., 2021) shows that for 3-ton unitary air conditioners, R-290 has the best performance compared to R-32, R-466A, R-452B, and R-410A. R-290 has about 12 percent higher COP across the full temperature range and about 4 percent higher COP than R-32 where a constant isentropic and volumetric efficiency compressor model is used. This said, it is reasonable to state that R-290 air conditioner designs could achieve at least the same efficiency levels as current R-410A air conditioners available on the market, with high potential for improved performance.

Equipment Cost Analysis Results

Equipment cost analysis for R-410A shifting to R-290 is presented. Equipment cost analysis for R-32 shifting to R-290 is included in Appendix C.

The additional parts for the primary safety system result in purchased-parts price increases of 3 percent and 4 percent for the Fujitsu and Midea air conditioners, respectively. The resulting purchased parts increase for the primary and redundant safety systems is 8 percent and 9 percent for the Fujitsu 2-ton mini split and Midea 1.5-ton window air conditioners, respectively. For details on the additional parts analysis, refer to Appendix C.

To translate the price increase in purchased parts into a manufacturer production cost (MPC) increase, U.S. DOE technical support documents (TSDs) for past air conditioner energy efficiency standards rulemakings were analyzed. The past U.S. DOE TSDs provide detailed information on disaggregated air conditioner MPCs, including the fraction of the MPCs represented by purchased parts. Using the MPC data from the TSDs indicates the increase in purchased parts prices established through the additional parts analyses can be translated into an overall increase in the MPC.

To estimate the MPC increase for the Fujitsu mini-split air conditioner analyzed here, the U.S. DOE TSD for the 2016 central air conditioner and heat pump energy efficiency standards (direct final rulemaking) was used (U.S. DOE, 2016). In the TSD, the MPCs for a 2-ton central air conditioner are provided. Because a 2-ton central air conditioner is relatively close in cooling capacity to the Fujitsu mini-split air conditioner, the MPCs of the 2-ton central air conditioner were assumed to be representative of the Fujitsu mini-split air conditioner's MPCs. Table 13 shows how the 2-ton central air conditioner MPCs were utilized to estimate the MPC increase of the Fujitsu mini-split air conditioner charged with R-290. The left side shows the MPCs of 2-ton 14 SEER (seasonal energy efficiency rating) and 21 SEER central air conditioners, including the fraction that is comprised of purchased parts. The middle of Table 13 shows how the 3 percent and 8 percent increases in purchased parts for an R-290 mini-split air conditioner (incorporating leak detection and unit control) are translated into a purchased part increase of $8.79 and $23.09, respectively. Note that the safety equipment is essentially a fixed cost for R-290 units, which does not scale with either equipment efficiency or capacity. The compressor cost increment for R-290 is added from an earlier UNIDO study (UNIDO, 2014), and the factory upgrade cost per unit (Colburne et al., 2011) is also added, as described in Chapter 2. The refrigerant cost savings are estimated assuming refrigerant costs of $4.21/kg of R-410A and $3.72/kg of R-290, and the R-290 charge in kg is 30 percent of the R-410A charge (UNIDO, 2014). In the case of the Fujitsu mini-split air conditioner, the overall MPC increase is estimated to be in the range of 0.8 percent to 1.6 percent for a primary safety system, and 1.8 percent to 3.8 percent for a primary and redundant safety system.

Table 13: R-290 Fujitsu Mini-Split Air Conditioner Manufacturer Product Cost Increase From R-410A

	2-ton Central Air Conditioner MPCs*							Adjusted MPCs for R-290 Fujitsu Mini-Split						
	Materials													
SEER	Total	Purch. Parts Frac.**	Labor	Overhead	Deprecia-tion	Total MPC	R-290 Safety: Purch. Parts Increase	R-290 Purch. Parts Incr.	Compress-or cost increment	Factory upgrade cost (Colburne et al. 2011)	Refrigerant impact (assuming R-410A reference)	MPC incremental cost assuming R-410A ref	Adj. MPC assuming R-410A reference	Percent inc. in MPC for R-290 assuming R-410A reference
Primary Safety System														
14	$520	$276	$81	$15	$32	$648	3%	$8.79	$7.57	$0.30	-$6.19	$10.47	$658	1.6%
21	$1,168	$619	$117	$19	$59	$1,362	-	$8.79	$7.57	$0.30	-$6.19	$10.47	$1,372	0.8%
Primary and Redundant Safety Systems														
14	$520	$276	$81	$15	$32	$648	8%	$23.09	$7.57	$0.30	-$6.19	$24.77	$673	3.8%
21	$1,168	$619	$117	$19	$59	$1,362	-	$23.09	$7.57	$0.30	-$6.19	$24.77	$1,387	1.8%
													avg	2.8%

Purchased parts fraction is 53 percent of total materials cost.

Sources: U.S. DOE TSD, Residential Central Air Conditioners and Heat Pumps, Direct Final Rule. Chapter 12, Section 12.3.5. December 2016, Authors' calculations. U.S. DOE TSD, Residential Clothes Dryers and Room Air Conditioners, Direct Final Rule. Chapter 5, Section 5.6.2.3. April 2011

To estimate the MPC increase for the Midea window air conditioner analyzed, the U.S. DOE TSD for the 2011 room air conditioner energy efficiency standards direct final rulemaking was used (U.S. DOE, 2016). In the TSD, the MPCs for three cooling capacity levels (specifically less than 6000 Btu/hr, 8000 to 13,999 Btu/hr, and 20,000 to 24,999 Btu/hr) are provided. The MPCs of all three capacity levels were assumed to be representative of the Midea window air conditioner's MPCs. Table 14 shows how the window air conditioner MPCs were used to estimate the MPC increase of the Midea window air conditioner charged with R-290. The left side of the table shows the MPCs of the three capacity levels of window air conditioners, including the fraction that is comprised of purchased parts. The middle of the table shows how the 3 percent and 8 percent increases in purchased parts for an R-290 window air conditioner (incorporating leak detection and unit control) are translated into a purchased part increase of $4.83 and $10.87 respectively for each cooling capacity level. As with the mini-split, the compressor cost increase, factory upgrade cost per unit, and savings from refrigerant charge are then added. In the case of the Midea window air conditioner, the MPC increase is estimated to range from 1.8 percent to 6.4 percent for a primary safety system and 3.4 percent to 9.9 percent for a primary and redundant safety system.

Table 14: R-290 Midea Window Air Conditioner Manufacturer Product Cost Increase From R-410A

Cooling Capacity (kBtu/h)	Window Air Conditioner MPCs*						R-290 Safety: Purch. Parts Increase	Adjusted MPCs for R-290 Midea Window AC						
	Materials													
	Total	Purch. Parts Frac.**	Labor	Overhead	Deprecia-tion	Total MPC		R-290 Purch. Parts Incr.	Compressor cost increment	Factory upgrade cost (Colburne et al. 2011)	Refrigerant impact (assuming R-410A reference)	MPC incremental cost assuming R-410A ref	Adj. MPC assuming R-410A reference	Percent inc. in MPC for R-290 assume R-410A reference
Primary Safety System														
<6	$116	$62	$24	$24	$7	$173	-	$4.83	$7.57	$0.30	-$1.55	$11.15	$184	6.4%
8-13.9	$149	$79	$31	$20	$9	$209	-	$4.83	$7.57	$0.30	-$3.09	$9.60	$219	4.6%
20-24.9	$277	$147	$43	$27	$16	$363	4%	$4.83	$7.57	$0.30	-$6.19	$6.51	$370	1.8%
Primary and Redundant Safety Systems														
<6	$116	$62	$24	$24	$7	$173	-	$10.77	$7.57	$0.30	-$1.55	$17.09	$190	9.9%
8-13.9	$149	$79	$31	$20	$9	$209	-	$10.77	$7.57	$0.30	-$3.09	$15.55	$225	7.4%
20-24.9	$277	$147	$43	$27	$16	$363	9%	$10.77	$7.57	$0.30	-$6.19	$12.45	$375	3.4%
													avg	6.9%

*Sources: U.S. DOE TSD, Residential Clothes Dryers and Room Air Conditioners, Direct Final Rule. Chapter 12, Section 12.4.6.2. April 2011, Authors' calculations
**Purchased Parts Fraction is 53 percent of total materials cost. Source: U.S. DOE TSD, Residential Clothes Dryers and Room Air Conditioners, Direct Final Rule. Chapter 5, Section 5.6.2.3. April 2011.

The calculations performed for both air conditioners demonstrate that the average manufacturer production cost increases for a combined primary and redundant safety system are approximately 3 percent and 7 percent, respectively. For the following life cycle cost analysis and net-impact analysis, MPC cost increases of 3 percent, 5 percent, and 7 percent are assumed to be representative for incorporating R-290 in current mini-split air conditioner, window air conditioner, and PTAC designs with R-410A refrigerant. We approximate the MPC cost increase for the PTAC as the average of the mini-split and window air conditioner increase since the average purchase price and capacity of PTAC are intermediate between these two AC types.

Installation Changes

Changes in installation practices to handle air conditioning equipment charged with R-290 come in the form of additional training for technicians/installers as well as the additional time required to safely install the equipment.

Becker, Munzinger, and de Graaf identify additional measures that technicians and installers need to take to install R-290 charged air conditioning equipment (Becker et. al., 2019). Those additional measures include: (1) creating a safe environment in case refrigerant leaks occur, which requires that before unit installation, a hazard analysis and risk assessment be conducted (specifically check the surrounding areas to ensure a spark free/non-flammable zone); (2) creating a safety work area, which includes setting up warning signs for the flammable work zone that is generally a 3-meter working area; and (3) using a combustible gas detector for system installation to detect any refrigerant leaks. All other installation practices remain unchanged and should already adhere to established HVAC technician training guidelines.

These additional measures impact the amount of time required to install an air conditioner. But because both window air conditioners and PTACs are factory charged, it is assumed no additional installation time is required for these air conditioner types. On the other hand, mini-split air conditioners are charged in the field and incur additional installation time. Because HVAC technicians should be familiar with current installation practices (such as those that would be required for the handling of A3 refrigerants), it is assumed that no more than an hour over current installation times would be required to install air conditioning equipment charged with R-290. Using data from RS Means (RS Means, 2020), the additional hour of technician time results in an additional installation cost of $177 for standard commercial installations and $124 for residential installations. For details on the increased installation cost determination, refer to Appendix C. Again, the increased installation costs apply only to mini-split air conditioners.

Cost Summary

The cost analysis conducted here indicates that R-290 mini-split, package terminal, and window air conditioners would incur an MPC increase relative to R-410A based designs of approximately 3 percent, 5 percent, and 7 percent, respectively for the incorporation of primary and redundant safety systems. In addition, it was estimated that mini-split air conditioners, because they are charged and installed in the field, could incur an additional installation cost ranging from $124 to $177 relative to R-410A based systems. Window air conditioners and PTACs would incur no additional installation cost because both air conditioner types are factory charged.

These cost estimates may represent the higher end of incremental equipment costs for small air conditioner units with R-290 based on safety system requirements, cost reductions from higher production volumes, the potential for some consolidation or simplification of safety system components, and examples from small self-contained commercial refrigeration equipment.

For example, small CRE does not have additional safety sensors or pressure transducers with a R-290 charge limit of 150 grams, which corresponds to U.S. EPA air conditioning maximum capacities of up to about 0.48 ton for window ACs, and up to about 0.83 tons for PTACs.

Other lower cost methods for detecting actual refrigerant charge in HVAC systems have also been described in the patent literature, without the pressure sensors assumed in the cost analysis just described (Gao et. al., 2018).

Life Cycle Cost (LCC) Results

Results from the LCC analyses for the scenarios considered are summarized in Table 14 and Table 15. From the equipment cost analysis for R-410A to R-290, the manufacturer price increases are 7 percent, 5 percent and 3 percent for window AC, PTAC/HP, and MSHP, respectively. These products are sold through retail outlets, contractors and installers, who mark up the manufacturer price to cover their own costs. The effect on retail price is calculated using incremental markups taken from the U.S. DOE rulemaking documents for each product. Incremental markups account only for those retail distribution chain costs that are affected by a change in the manufacturer selling price. For the R-32 to R-290 scenario it is assumed that the manufacturer price increase would be one-half of the increase in the R-410A scenario (Appendix C).

Window AC has the smallest cost increase in absolute terms, but the largest in percentage terms. In all cases the absolute price increase is relatively small, and could potentially be offset by product-type consumer rebates. These consumer rebates are estimated amounts in the current year (2021), with cost-analysis assumptions and differential amounts (and concomitant rebates) that could drop over time as production of R-290 units is ramped up and unit costs reduced from economies of scale and technology advances. Note the total installed cost (TIC) does not depend on any variables selected from a distribution, so a rebate would be a one-time fixed payment.

Table 15: Total Installed Costs (TIC) for the Baseline, R-410A to R-290, and R-32 to R-290 Scenarios

	Mini-split HP		PTAC		PTHP		Window AC	
	TIC	Change in TIC	TIC	Change in TIC	TIC	Change in TIC	TIC	Change in TIC
Baseline	$3,825	-	$1,443	-	$1,580	-	$440	-
R-410A to R-290	$3,900	$75	$1,486	$43	$1,626	$46	$466	$26
R-32 to R-290	$3,862	$37	$1,465	$21	$1,603	$23	$453	$13

Source: Author calculations

The sample average LOX results for the three product use scenarios are summarized in Table 16. Unlike the TIC, the LOX depends on several variables (including annual operating hours, discount rates and product lifetimes) drawn from distributions. Hence, there is broad diversity in the actual operating expense across the consumer sample, as illustrated in Figure 20. This figure shows the distribution of LOX results for window AC. The data are binned, with bin width of $25; the horizontal axis label is the bin mid-point. The primary driver on the variability in LOX is the variability in operating hours.

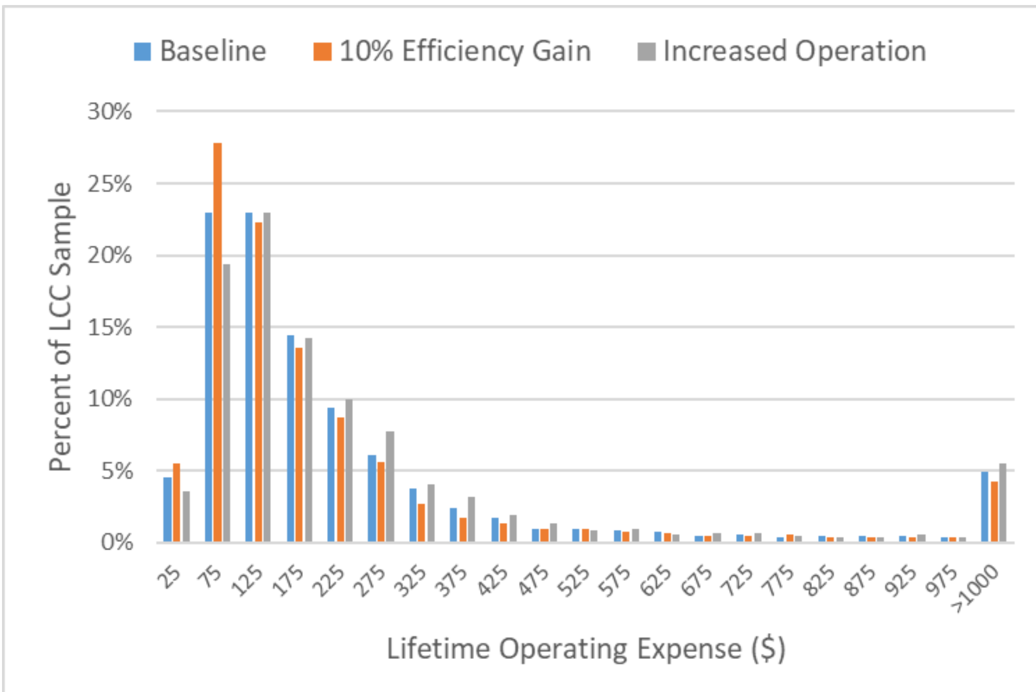
Table 16: Scenarios for Sample-Average LOX Results for Equipment Type

	Mini-split HP		PTAC		PTHP		Window AC	
	Annual kWh	LOX	Annual kWh	LOX	Annual kWh	LOX	Annual kWh	LOX
Baseline	839	$2,961	697	$1,056	747	$1,115	134	$367
10% efficiency	763	$2,695	634	$961	679	$1,014	122	$334
Warmer								
Climate	908	$3,207	766	$1,162	810	$1,213	147	$404

Equipment type in the Baseline, 10-percent Efficiency Gain, and Warmer Climate Scenarios

Source: Author calculations

Figure 20: Distribution of Lifetime Operating Expense (LOX) for Window AC



Lifetime operating expense in the Baseline, 10-percent Efficiency Gain, and Warmer Climate Scenarios

Source: Author calculations

California Net Impact Analysis

GHG Scenarios and Potential Savings for 2030 and 2050

Greater Low-GWP Air Conditioner Adoption Scenario

The primary GHG benefit in this analysis is the switch from R-410A or R-32 to R-290 refrigerants. Global warming potential is used to measure the climate benefits of R-290 relative to R-410A. GWP measures the climate damage of various substances relative to CO_2 (which has a GWP of 1). The GWP of R-410A is 2,088, the GWP of R-32 is 675, and the GWP of R-290 is 3.3

(CARB, 2021). Therefore, a transition to R-290 will have a significant climate benefit through the reduction of global warming gases from HVAC systems.

Refrigerant is lost in two ways in this modeling, annual leakage and end of life leakage. Annual leakage comes from small amounts of refrigerant that escapes during operation and end of life leakage occurs when an air conditioner is disposed of and the refrigerant is not properly removed. Table 17 shows the total charges by refrigerant, percentage of annual leakage, and percentage of end-of-life leakage assumed for PTACs/PTHPs, window ACs, and mini-splits. The total charges in the table come from testing data from this project and other studies (Abdelaziz et al., 2015; Pham and Rajendran, 2012; Schultz, 2016; and ACR, 2013). The annual leakage rates for PTACs/PTHPs and window AC along with the end-of-life leakage for all equipment were taken from the CARB (Gallagher, 2015). The annual leakage rates for mini-splits were taken from a city of Seattle refrigerant report (PAE Engineers, 2020).

Table 17: Assumed Refrigerant Charges and Leakage, by Product

Equipment	Capacity (Btu/hr)	Total Charge R-290 (lbs)	Total Charge R-410A (lbs)	Total Charge R-32 (lbs)	Annual Leakage	End-of-Life Leakage
PTAC / PTHP	9,000	0.84	1.26	1.01	2%	100%
Window AC	8,000	0.74	1.12	0.89	2%	100%
Mini-Splits	18,000	2.48	3.72	2.98	5%	80%

Source: Gallagher 2015, Abdelaziz et al., 2015, Pham and Rajendran 2012, Schultz 2016, and ACR 2013

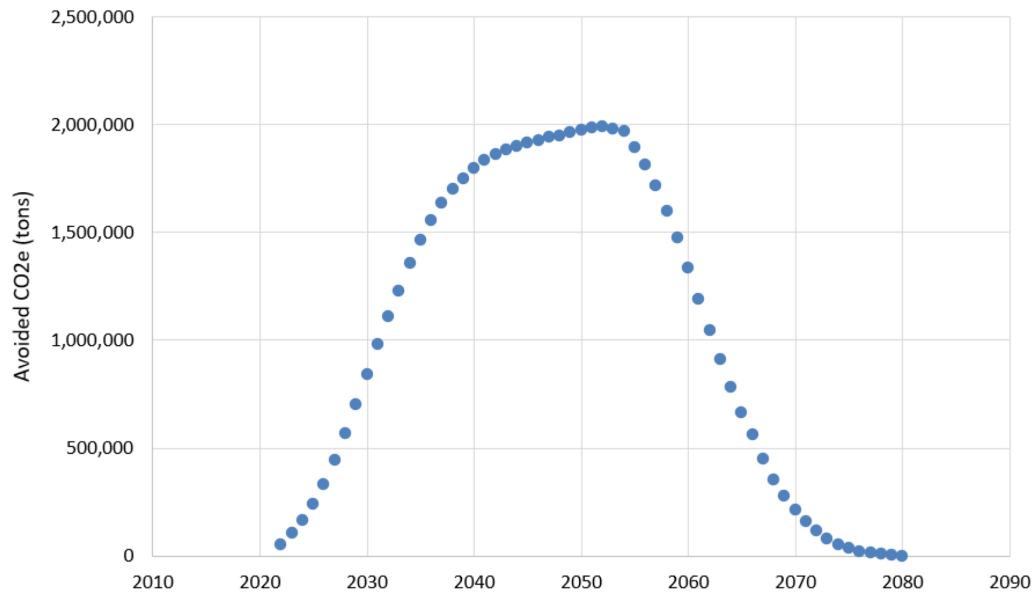
It was assumed that PTACs/PTHPs and window ACs would not have refrigerant replenished through the lifetime of the product, so the end-of-life refrigerant is equal to:

Total refrigerant charge (pounds [lbs]) – (Annual leakage [lbs] x lifetime).

For mini-splits, it was assumed that the refrigerant was recharged every five years, so the end-of-life refrigerant will vary between a full charge and 75 percent of a full charge.

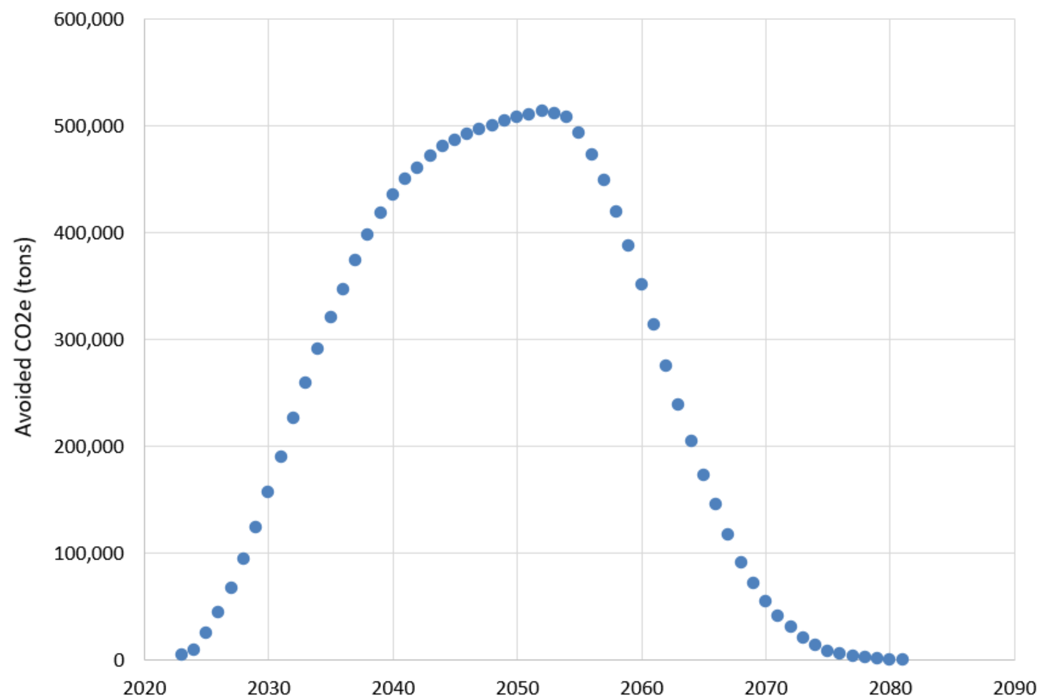
The climate benefit from R-290 is measured by comparing the amount of leaked refrigerants in a year with the difference in GWP between R-290 and either R-410A or R-32. The total amount of avoided CO_2e from refrigerant emissions is equal to the annual leakage across the existing stock in a given year, plus the avoided end of life leakage of units that fail in a given year. Figure 21 and Figure 22 display the avoided CO_2e (in tons) for the transition to R-290 from the two baseline refrigerants.

Figure 21: Avoided CO_2e From R-290 Compared to R-410A



Source: Author calculations

Figure 22: Avoided CO_2e From R-290 Compared to R-32



Source: Author calculations

Table 18 shows the annual and cumulative avoided refrigerant emissions in tons of CO_2e for R-410A to R-290 and R-32 to R-290.

Table 18: Annual and Cumulative Avoided Refrigerant Emissions

Year	R-410A to R-290		R-32 to R-290	
	Annual Avoided Emissions (tons CO_2e)	Cumulative Avoided Emissions (tons CO_2e)	Annual Avoided Emissions (tons CO_2e)	Cumulative Avoided Emissions (tons CO_2e)
2030	840,314	3,448,463	156,400	525,423
2050	1,972,549	37,182,436	507,733	8,635,456

Source: Authors' calculations

Table 19 displays the breakdown of avoided refrigerant emissions in tons of CO_2e by product in 2030 for R-410A to R-290.

Table 19: Avoided Refrigerant Emissions in Tons of CO_2e by Product in 2030 (R-410A to R-290)

	PTAC	PTHP	Window AC	Mini-Split
Annual	62,325	50,879	358,842	368,267
Cumulative	227,596	183,507	1,365,351	1,672,010

Source: Author calculations

Starting in 2023, all small AC in California must have refrigerants with GWP less than 750 (central systems must comply beginning in 2025). It is assumed that PTACs, PTHPs, and window ACs would qualify as small AC and transition to R-32 (GWP=675) in 2023 and mini-splits will transition to R-32 in 2025. In this case of R-32 as the new "lower GWP" baseline, a transition to R-290 will have smaller savings in avoided direct emissions. For the case of transitioning from a baseline of R-32 to R-290, the cumulative avoided emissions in 2050 are reduced to 8,635,456 tons of CO_2e from 37,182,436 when using R-410A as the baseline.

Table 20 shows the NPV for the next 30 years for shifting to R-290 refrigerant from either a R-410A baseline or an R-32 baseline. For the R-32 baseline, there is an additional cost of $217 million to switch to R-290; for R-410A baseline there is an additional cost of $452 million to switch to R-290. For R-32, the avoided direct emissions for the full equipment lifetimes to 2080 are 15.1 MMT CO_2e while for R-410A, the savings are 61.9 MMT CO_2e. Equipment costs are tracked for the next 30 years but avoided refrigerant emissions extend to 2080 to track equipment emissions from units sold prior to 2050 but are still in the field after 2050. This corresponds to a cost per ton-CO_2e saved of $14.37 and $7.31, respectively.

Table 20: Cost per Ton of CO_2e Saved for R-290 Versus R-32 and R-410A

Baseline refrigerant	NPV (millions$)	Avoided refrigerant (million tons CO_2e)*	Cost per MT CO_2e saved ($)
R-32	-217	15.1	14.37
R-410A	-452	61.9	7.31

***Avoided refrigerant emissions timeframes extend through 2080 to account for equipment lifetime of installed equipment.**

Source: Author calculations

High-Efficiency Air Conditioner Adoption Scenario

In these scenarios, it is assumed that the low-GWP refrigerants are used in equipment that is 10 percent more efficient than the current federal baseline (Table 21) and that equipment costs are 10 percent higher than the baseline refrigerant. Resulting environmental benefits include avoided refrigerant emissions, reduced purchased electricity from utilities, and consumer utility bill savings.

Table 21: Energy Efficiency Assumptions for Higher Efficiency Case

Product	Baseline EER	Baseline UEC (kWh)	High Efficiency EER	High Efficiency UEC (kWh)
PTAC	11.3	697	12.4	634
PTHP	11.3	747	12.4	679
Window AC	10.9	134	12	122
Mini-Split HP	12.2	839	13.4	763

Source: Author calculations

In the base case scenario, it is assumed that all units shipped are at the baseline EER over the 30-year analysis period, and that the equipment cost between a unit with R-410A or R-32 refrigerant is compared to the equipment cost of a unit with R-290 refrigerant and the same EER. In the high efficiency case, it is assumed that all units are shipped at the high-efficiency EER. The energy savings and economic benefits are calculated by comparing total equipment costs and energy use for both baseline and high-efficiency scenarios over the 30-year analysis period. Economic benefits are calculated with two discount rates: 3 percent and 7 percent. A 3-percent annual growth trend is used to project electricity prices through 2050, at which point electricity prices remain constant at 2050 levels. The unit energy consumption is the energy consumption at the site. To calculate the total energy saved, it is important to account for site energy use as well as energy losses associated with the generation, transmission, and distribution of electricity, as well as energy consumed in extraction, processing, and transporting energy (referred to as full-fuel-cycle electricity use). For this, the team used a full-fuel-cycle multiplier from AEO 2021 that is applied to the site electricity savings in each year of the analysis period.

To calculate the reduction in emissions from energy efficiency, the amount of energy saved in each year of the analysis period, relative to the baseline efficiency, and multiplied by an emissions factor (lbs of CO_2e/kWh) for the state of California. The emissions factor is the weighted average of the emissions per kWh across different times of day and different fuel mixes used to generate electricity within the state. California's grid is becoming cleaner each year, which means that the emissions factor is falling over time. In this report, it was estimated the annual emissions factors using an E3 consulting report (Mahone et al., 2020), which estimated the emissions factor through 2050 using the SB 350 scenario.[7] Table 22 displays the annual electricity and CO_2e savings from a 10 percent gain in efficiency in select years over the course of the 30-year analysis period. Table 23 and Table 24 provide the net present value (NPV) at 3 percent and 7 percent discount rates, along with the cumulative site and full-fuel-cycle electricity savings from the 10 percent increase in efficiency (Table 25).

Table 22: GHG Savings From Electricity Sector (for R-410A to R-290 Case)

Year	Annual GWh saved	Annual CO_2e saved (tons)
2025	627	138,327
2030	651	129,178
2035	670	133,036
2040	678	134,510
2045	698	130,802
2050	722	143,309
Total	**20,116**	**4,051,187**

Source: Author calculations

Table 23: R-410A Base Case Economic Benefits From Energy Savings by Product, Over 30 Years

	PTAC	PTHP	Window AC	Mini-Splits	Total
7% discount rate: Net Present Value (Millions of 2020$)	$44.6	$39.4	$93.0	$385.3	$562.4
3% discount rate: Net Present Value (Millions of 2020$)	$113.8	$100.1	$297.8	$1,002.7	$1,514.5
Site Electricity Savings (quads)	0.003	0.002	0.006	0.013	0.025
Full Fuel Cycle Electricity Savings (quads)	0.008	0.007	0.018	0.037	0.069

Source: Author calculations

[7] SB 350 established greenhouse gas reduction goals of 40 percent below 1990 levels by 2030 and 80 percent below 1990 levels by 2050. https://www.energy.ca.gov/rules-and-regulations/energy-suppliers-reporting/clean-energy-and-pollution-reduction-act-sb-350.

Table 24: R-32 Base Case Economic Benefits From Energy Savings by Product, Over 30 Years

	PTAC	PTHP	Window AC	Mini-Splits	Total
7% discount rate: Net Present Value (Millions of 2020$)	$69.3	$60.4	$204.1	$516.5	$850.3
3% discount rate: Net Present Value (Millions of 2020$)	$155.3	$135.5	$477.5	$1,232.1	$2,000.4
Site Electricity Savings (quads)	0.003	0.002	0.006	0.013	0.025
Full Fuel Cycle Electricity Savings (quads)	0.008	0.007	0.018	0.037	0.069

Source: Author calculations

Table 25: Total GHG Savings for Both Refrigerants

Baseline refrigerant	NPV, 7% discount rate (millions$)	Electricity grid GHG emissions saved (million tons of CO_2e)	Avoided refrigerant (million tons CO_2e)	Total GHG saved (MMT-CO_2e)	Cost per ton-CO_2e saved ($)
R-32	850.3	4.0	15.1	19.1	-44.52
R-410A	562.4	4.1	61.9	65.9	-8.53

[1]The electricity grid GHG emissions saved vary due to the different shipments analysis periods (2022-2051 for R-410A, 2023/25-2052/54 for R-32).

These show scenarios where R-290 AC units have 10 percent higher energy efficiency than baseline refrigerant over 30 years.

Source: Author calculations

In this case, the operational cost savings of R-290 generate $850.3 million in net savings compared to R-32 and $562.4 million in net savings over the 30-year time frame compared to R-410A. The relative savings of GHG emissions from the electricity grid is quite small compared to the savings of direct emissions of refrigerant at 21 percent and 6.6 percent of the total GHG savings from R-32 and R-410A baseline cases, respectively, since the California electricity grid has low and decreasing carbon intensity. There is a net savings and a negative cost for CO_2 saved, or a savings of $44.52 and $8.53 per ton of CO_2e saved for R-32 and R-410A, respectively.

To allow for the comparison of other high-efficiency policy scenarios, Table 26 provides the energy savings per unit, shipped over a product's lifetime with a 10 percent increase in efficiency. The energy savings does not change between the R-410A and R-32 baselines since the unit energy consumptions (UECs) are the same for both baseline and high-efficiency equipment.

Table 26: Energy Savings per Unit Shipped (in kWh) for a Product Lifetime in the High-Efficiency Case

PTAC	PTHP	Window AC	Mini-Splits	Total
875	944	268	1,943	682

Source: Authors' calculations

Alternate Scenarios: High Shipments and Increased Cooling Demand

Two other scenarios were modeled: a high shipments case for window AC and mini-splits over the 30-year analysis period, and a scenario where the cooling hours increase by 10 percent along with a heating hour decrease of 10 percent, to model the impact of a warming climate. Both scenarios were modeled with R-32 as the baseline refrigerant. Table 27 through Table 30 provides results for the alternate scenarios.

Table 27: Cost per Ton of CO_2e Saved for R-290 Versus R-32

Baseline refrigerant	NPV (millions$)	Avoided refrigerant (million tons CO_2e)	Cost per MT CO_2e saved ($)
High Shipments	-259	19.1	13.56
Increased Cooling	-217	15.1	14.37

In the high shipments and increased cooling in the equivalent efficiency case

Source: Author calculations

Table 28: High-Shipments Case - Economic Benefits From Energy Savings (R-32 Base Case)

	PTAC	PTHP	Window AC	Mini-Splits	Total
7% discount rate: Net Present Value (Millions of 2020$)	$36.25	$31.50	$138.79	$416.67	$623.2
3% discount rate: Net Present Value (Millions of 2020$)	$75.9	$66.0	$311.47	$988.76	$1,442.2
Site Electricity Savings (quads)	0.003	0.002	0.007	0.019	0.032
Full Fuel Cycle Electricity Savings (quads)	0.008	0.007	0.021	0.053	0.088

Source: Author calculations

Table 29: Increased Cooling Case - Economic Benefits From Energy Savings (R-32 Base Case)

	PTAC	PTHP	Window AC	Mini-Splits	Total
7% discount rate: Net Present Value (Millions of 2020$)	$40.7	$34.3	$147.2	$340.4	$562.6
3% discount rate: Net Present Value (Millions of 2020$)	$84.6	$71.5	$322.5	$772.3	$1,250.8

	PTAC	PTHP	Window AC	Mini-Splits	Total
Site Electricity Savings (quads)	0.003	0.003	0.007	0.014	0.027
Full Fuel Cycle Electricity Savings (quads)	0.008	0.007	0.020	0.040	0.075

Source: Author calculations

Table 30: Total GHG Savings for R-290 AC Units

Scenario	FFC quads saved	NPV, 7% discount rate (millions$)	Electricity grid GHG emissions saved (million tons of CO_2e)	Avoided refrigerant (million tons CO_2e)	Total GHG saved (MMT CO_2e)	Cost per ton-CO_2e saved ($)
High shipments	0.088	623.2	5.1	19.1	24.2	-25.76
Increased Cooling	0.075	562.6	4.4	15.1	19.5	-28.85

These units have 10 percent higher energy efficiency than baseline refrigerant over next 30 years in the high shipments and increased cooling cases (R-32 base case).

Source: Authors' calculations

Favorability Index

A "favorability index" for adoption of A-3 flammable refrigerants such as R-290 and propane are shown in Table 31 for the four product types considered. Four key criteria were considered: prospects for compliance with U.S. EPA 2015 charge limits, efficiency, cost increases (total lifecycle cost as described), and market size. For example, because testing has demonstrated that window ACs under 1-ton in cooling capacity could very likely be designed to comply with current U.S. EPA regulations, compliance with U.S. EPA 2015 charge limits is excellent. Because testing was not conducted for windows greater than 1-ton, compliance with U.S. EPA charge limits is moderate.

Note that flammability risk is not explicitly included in Table 31 because: testing and assessment of flammability risk was out of the project scope, data describing flammability risk across the product lifecycle were not readily available for all of the products tested, and proposed international safety standards set R-290 charge limits up to the maximum charge allowed by U.S. EPA 2015 and allow split systems. For the latter, the proposed IEC 60335-2-40 standard, 7th Edition, allows mini-split units with less than 150 grams of propane for standard systems. The proposed standard also allows split systems with increased charge limits of up to 998 grams of propane for systems with enhanced tightness and airflow circulation, and further allows up to 304 grams for factory-sealed movable AC units such as portable AC units and window AC units.

Three product types are tested in this project: PTACs, window AC units, and mini-split ACs. All products are considered to have excellent energy efficiency with R-290 based on both this study and earlier testing studies. R-290 as a drop-in refrigerant has equivalent to 10 percent higher EER, with a small single-digit reduction in cooling capacity. With small design changes, equivalent capacity can be achieved.

Table 31: Favorability Index for A3 Refrigerant (R-290, Propane)

Product	Tested in this project	Compliance with EPA 2015 charge limits	Efficiency	Cost Increase	Market size	Favorability per EPA 2015 charge limits
Small Self-Contained Commercial Refrigeration Equipment (CRE) and Domestic Refrigeration	No	Excellent	Excellent	Equiv. cost	Large	Excellent
Packaged Terminal Air Conditioners	**Yes**	Low	Excellent	Equivalent to slight increase	Moderate to Small	Moderate to Low
Window Air Conditioners (≤ 1-ton)	**Yes**	Excellent	Excellent	Equivalent to slight increase	Moderate	Excellent
Window Air Conditioners (> 1-ton)	No	Moderate	Excellent	Equivalent to slight increase	Moderate	Excellent to Moderate
Mini-split Air Conditioners	**Yes**	Not allowed*	Excellent	Equivalent to slight increase	Small	Low*

*Note that split systems are allowed under proposed international safety standard IEC 60335-2-40, 7th Edition, and that a 1-ton mini-split air conditioner with 380 grams of R-290 was expected to be commercially available in Europe in 2020 but was delayed by the COVID-19 pandemic (Cooper, 2020).

Source: Author assessment

Equivalent to a slight increase in cost is estimated for all RAC product types. The equipment cost estimates shown here are viewed as high-end estimates (per expert advisor Omar Abdelaziz) and realistic equipment cost increases are expected to be in low single-digit percentages for all four product types.

The most favorable products for A3 refrigerants are small self-contained CRE, domestic refrigeration, and small-capacity window air conditioners that are also self-contained. The self-contained nature of these products makes a large-scale refrigerant leak less likely than equipment types that are installed in the field, such mini-split air conditioners.

Small CRE with A3 refrigerants is widely available on the marketplace today, and an estimated 100 million domestic refrigerators with A3 refrigerants have already been installed globally.

- **Packaged Terminal Air Conditioners** have a higher relative flammability risk since these units are typically installed very low to the ground. Leaking refrigerant therefore has greater chances to pool on the ground, with less distance and room to dissipate when moving from the leakage location to the ground. PTACs are generally found in hotels, and hotel owners may be particularly sensitive to liability issues in the case of fires linked to refrigerant leakage. Additionally, the market for PTACs is generally smaller than that for window ACs, which have a broader range of applications.

- **Window Air Conditioners** are the most promising candidate for A3 refrigerant replacement. They are installed higher above the floor than PTAC units and since they are usually hanging outside of the window there is less chance of any accumulation of refrigerant on the floor if there is a leak. Window ACs have larger annual unit sales volume than either PTACs or mini-split ACs. It is also possible that, due to climate change, the summer season could be hotter. More uncooled households will seek some form of additional cooling and window ACs are among the most affordable and easiest to install to meet this growing demand. Testing results also indicate that optimally designed small window air conditioners of less than 1-ton cooling capacity could meet current U.S. EPA maximum allowable R-290 levels. We did not test window ACs over 1-ton, and it is unclear whether these units can meet U.S. EPA regulations.
- **Mini-Split Air Conditioners** are typically high-efficiency ductless air conditioners with refrigerant lines to an outdoor condensing unit. They are typically charged onsite by technicians so there is greater risk for potential leakage due to insufficiently or incorrectly brazed joints. This product type is the least likely to attain regulatory approval for A3 refrigerants due to this concern. Mini-split ACs currently do not have a large market share in California. However, they can be a good candidate in some cases for retrofits to electric HP-based HVAC systems due to their compact form, high energy efficiency, and ability to replace two appliances (for example central air conditioning unit and gas-fired furnace unit). Mini-splits with A3 refrigerants are becoming more available in other parts of the world, including in India and China. Mini-split air conditioners with 1-ton cooling capacity were expected to be commercially available in Europe in 2020 (Cooper, 2020), but availability was delayed by the COVID-19 pandemic. Other innovative approaches might reduce the cost of installation and enable reduced refrigerant charge and reduced risks associated with mini-split heat pump field-installation, with flammable refrigerants in the future such as the EcoSnap air conditioner heat pump from the National Renewable Energy Laboratory (NREL, 2019).

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

The knowledge produced through this study is being shared in several ways. First, this report discusses the methods and results in detail and will be made available to other research, standards and codes, and installation teams.

The team shared project results with CARB to encourage regulatory approval paths for R-290 units by UL and other safety standards bodies; presented project results at a California Energy Commission (CEC) workshop entitled *Building Decarbonization and Refrigerants* on August 26, 2021, to an audience of stakeholders from the California Public Utilities Commission (CPUC) and from industry; and with energy efficiency standards and air conditioning development groups at LBNL.

The key target market for this technology in air conditioning is small window ACs of less than 1-ton cooling capacity. Longer term markets could be mini-split ACs and mini-split heat pumps. The current and anticipated market for window ACs in California is annual shipments of 622,000 units in 2022 increasing to 675,000 in 2050. The current and anticipated market for mini-split units is annual shipments of 171,000 units in 2022, increasing to 197,000 in 2050.

The key barriers are regulatory barriers to R-290 use in AC equipment. The current UL standard UL 484 (UL 60335-2-40) limits the charge size of R-290 to 114 grams (UL, 2014; UL, 2019). This report will help stimulate market interest for room ACs with R-290 by showing its climate benefits in small ACs, and by encouraging safety standards bodies to increase charge limits for R-290 above the current UL limit. Cost analysis for equipment cost, including life-cycle cost and cumulative impact analysis, informs policymakers the climate benefits and costs of small AC equipment.

The technical advisory committee for this project included stakeholders from industry, government agencies, and technical experts. Through their participation in this project they have helped in the development of assumptions, and have reviewed results as they were developed and finalized. This will ensure that they understand the benefits of this work and that project results can be used to direct future programs and studies.

Finally, LBNL anticipates publishing the results of this analysis in a journal in late 2023/early 2024. This will make the data, methods, and results of this work broadly available to research, development, and deployment communities at both national and international levels. In addition to communicating and archiving the key findings of this work to a wider audience, this publication will also provide an opportunity to highlight key areas and opportunities to stakeholders for further reductions and other important follow-up work (for example, lower costs, higher energy efficiency designs and market development programs).

CHAPTER 5: Conclusions/Recommendations

Flammable Class A3 refrigerant hydrocarbon gases such as propane have significantly lower-GWP value than conventional HFC refrigerants. They are widely available and have good refrigerant properties for both refrigeration and air conditioning equipment. The key concern for A3 refrigerants is their flammability, which must be carefully managed in equipment design, manufacturing, maintenance and repair could also pose some risk to the consumer if there is a refrigerant leak during the equipment's operating life. U.S. EPA 2015 states that concern of flammability risks with hydrocarbon refrigerants can be adequately managed through proper design, controls, and use conditions.

Small, self-contained refrigeration and air conditioning units comprise the most accessible market segment for flammable refrigerants because the equipment's refrigerant is installed (charged) at the factory, the equipment is in an enclosed box without exposed refrigerant lines, and refrigerant quantities (or charge sizes) are relatively small (no more than 150 grams in commercial refrigeration units. Room air conditioning units that are installed higher above the floor can support more refrigerant charge and are less of a safety risk.

Refrigeration equipment with propane (R-290) is widely available already for small self-contained commercial equipment in the U.S. More than 400 million hydrocarbon refrigerators have been installed worldwide and millions of small residential AC units using hydrocarbons or mildly flammable R-32 are also in use worldwide, and reports of refrigerator ignition incidents attributed to leaked hydrocarbons have been rare (U.S. EPA, 2015). Full sized domestic refrigerators with hydrocarbon refrigerant have been available since 2022.

This project provides (1) modeling of optimized designs, (2) testing results of window AC, PTAC, and mini-split AC units with R-290, (3) cost analysis of incremental equipment costs and life-cycle costs for R-290 versus baseline HFC units, and (4) net impacts in GHGs and consumer costs for California over the next three decades.

Numerical models for small air conditioning units were developed to better understand the energy performance of AC systems from both system and component levels. Key sensitivity parameters modeled included subcooling, superheating, heat exchanger design for indoor and outdoor units, and fan power. The optimal window AC design achieves a 6.8 percent power consumption decrease and a 3.5 percent cooling capacity increase compared to the R-22 baseline, which shows an 11.1 percent system EER improvement. This translates to a 24.1 percent EER improvement from the original R-22 baseline. Similarly, the optimal mini-split AC design achieves a 5.3 percent power consumption decrease and a 4.8 percent cooling capacity increase compared to the R-22 drop-in, which gives a 10.7 percent system EER improvement. This translates to a 20 percent EER improvement from the original R-22 baseline.

The cost analysis conducted here indicates that R-290 mini-split, room, and package terminal air conditioners would incur a manufacturer production cost increase relative to R-410A based designs of approximately 3 percent, 5 percent, and 7 percent, respectively, for the incorporation of primary and redundant safety systems or $26 to $75.

Project testing indicates that small window ACs less than 1 ton in capacity can have refrigerant charge at or less than the U.S. EPA 2015 limit, with equivalent to slightly improved efficiency and equivalent to slightly lower cooling capacity to the reference R-22 refrigerant case (and by extension to baseline HFC refrigerant R-410A. Similar testing results were obtained for packaged terminal AC units and mini-split air conditioners).

Small window ACs with R-290 thus represent the most favorable point of market entry for room ACs with R-290 since they are self-contained units, can meet the U.S. EPA 2015 charge limit, and have room for further performance improvements. PTACs with R-290 are less favorable for market entry since the units tested did not meet U.S. EPA charge limits and PTACs are typically installed lower to the ground than window ACs. Mini-split heat pumps with R-290 are not currently allowed by the U.S. EPA since refrigerants are installed onsite, are not self-contained, and have the highest relative risk for R-290 leakage.

However, the current UL 484 (UL 60335-2-40) limit of 114 grams or less of R-290 per AC unit (UL, 2014; UL, 2019) is a much tighter limit than U.S. EPA 2015 limits for all but the smallest units, and does not consider varying room sizes and installation heights. This precludes room ACs with R-290 from being developed for the room AC market in California. In October 2020, international safety standards in Europe approved a proposal for higher refrigerant charge limits, with maximum R-290 charge up to the maximum charge allowed by U.S. EPA 2015 in air conditioning systems (up to 0.998 kg), and commercial availability of mini-splits with 0.380kg of R-290.

Statewide modeling for California indicates the potential to save a cumulative 8.6 or 37.2 MMT from room air conditioning over the next 30 years, at less than $15 cost per ton of CO_2e saved (assuming that R-290 units are available on the market relative to either a R-32 or R-410A refrigerant baseline).

For window air conditioners with R-290 and the same energy efficiency as baseline R-410A refrigerant and a 7 percent increase in cost, the life-cycle cost increase is $26 or about 3 percent higher in total lifecycle cost. Therefore, a subsidy or rebate program that refunded the buyer $26 of the unit purchase price would be enough to ensure that most consumers receive a neutral economic impact under this scenario. This is likely to be an upper-end estimate since the equipment component cost analysis included some components that either may not be required or may be available at lower cost. With design optimization, units with R-290 may also have higher efficiency than the baseline refrigerant.

The project team estimates a cumulative potential savings of 8.6 to 37.2 MMT CO_2e over the next 30 years in transitioning to small room AC with R-290 refrigerant, at a net cost of about $14 to $7 per ton of saved CO_2e (with a 10 percent higher equipment cost and equivalent efficiency to baseline HFC refrigerants R-410A and R-32). In this case, all GHG savings are from direct emissions savings. For the sensitivity case of 10 percent higher efficiency with R-290, there is a net savings of switching to R-290 from R-410A and R-32, or $8.53 and $44.52 per ton of saved CO_2e, respectively, over the next 30 years since savings from lower electricity costs outweigh slightly higher equipment costs. In this case, direct emission savings from refrigerant transition are about six times higher than indirect savings (from electricity grid GHG) since the California electricity grid is becoming very low in carbon intensity.

Some gaps are highlighted for the use of room ACs with R-290. The first barrier is the lack of harmonized policy signals and market incentives that manufacturers can pursue in small window air conditioners. Harmonized policy between UL safety standards and charge limits of U.S. EPA would provide a clear signal to manufacturers for small room ACs, with acceptable designs that could be followed by incentives, rebates, or other "market-pull" mechanisms to encourage market expansion.

It is also noted that existing leak testing and ignition testing is typically for worst-case leakage in PTAC and mini-split ACs and do not address the question of how probable these leakage events are or could be. The research team did not find leak testing and ignition testing specific to window air conditioners, so these could be areas for further study.

Technician training and certification for the safe handling of flammable refrigerants would be helpful for market development, as would the development of an industry standard for hydrocarbon recovery equipment.

From a technical standpoint, more optimized design work, cost analysis, and integrated room AC designs within the room (for example PTACs designed for mounting higher above the ground or above windows) can further improve unit-level performance and reduce the risks of refrigerant leakage

CHAPTER 6: Benefits to Ratepayers

High-GWP refrigerants are the fastest-growing GHG sector in California, and cost-effective approaches that sharply reduce emissions in this sector are urgently needed. Climate-friendly and cost-effective AC units are therefore important to support the state's mandates for more energy equity and resilience. With a warming climate, energy-efficient small air conditioning units with very low GHG emissions are even more important to provide comfort during hot weather.

This report demonstrates that room air conditioners with R-290 are cost-effective for GHG mitigation, resulting in substantial GHG savings with a low cost per ton of CO_2e saved, at an estimated $14.50 to $44.50 per ton of saved CO_2e over a 30-year time frame. GHG savings are driven by more than 99 percent reduction in direct emissions compared to conventional HFC-based refrigerants.

It is estimated that residents in California could save up to 66 MMT CO_2e emissions over the full equipment lifetimes (to 2080), compared to a baseline of R-410A refrigerant and 19.1 MMT CO_2e (compared to a baseline of R-32 refrigerant).

Small air conditioning units with R-290 refrigerants can be adopted in small commercial buildings or residential buildings most readily in window AC units. High-end cost estimates for the incremental cost of equipment with R-290, over units with baseline R-410A refrigerant, are an average of $37 additional per unit over the lifetime of the unit (or less than a 3.5-percent increase in life-cycle costs).

Introducing market entries in the room AC market with R-290 refrigerants would also give consumers greater choice when choosing climate-friendly ACs. Room ACs with R-290 would reduce direct CO_2e emissions by 99.51 percent compared to R-32 and by 99.84 percent compared to R-410A.

This work sets the groundwork for state policy to support R-290 in small room AC units, to develop demonstration projects and programs with R-290 room AC units (in partnership with AC vendors), and further explore room AC design optimization based on this project's modeling work. As a first step, increasing UL charge limits and other safety standards to be more consistent with IEC and U.S. EPA standards would enable more industry activity for R-290-based air conditioners.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
°C	degrees Celsius
°F	degrees Fahrenheit
AC	air conditioning or air conditioner
AEO	Annual Energy Outlook
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AIM Act	American Innovation and Manufacturing Act
AREP	(Low-GWP) Alternative Refrigerants Evaluation Program
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BOM	bill of materials
BSRIA	Building Services Research and Information Association
Btu/hr	British thermal units per hour
CARB	California Air Resources Board
CEC	California Energy Commission
CFC	chlorofluorocarbon
cm/s	centimeters per second
CO_2	carbon dioxide
CO_2e	CO_2 equivalent (usually used in the context of the CO_2 equivalent in global warming potential for a non-CO_2 greenhouse gas such as propane)
COP	coefficient of performance
CPUC	California Public Utilities Commission
CRE	Commercial refrigeration equipment
DC	direct current
EE	energy efficiency
EER	energy efficiency rating
g/m^3	grams per cubic meters
GHG	greenhouse gases
GUI	graphical user interface
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HFO	hydrofluoroolefins

Term	Definition
HP	heat pump
HVAC	heating, ventilation, and air conditioning
IEC	International Electrotechnical Commission
kg	kilograms
kg/s	kilograms per second
kWh	kilowatt-hours
LBNL	Lawrence Berkeley National Laboratory
lbm/hr	pound mass per hour
lbs	pounds
LCC	life-cycle cost
LOX	lifetime operating expense
mini-split air conditioner	small AC unit with a separate evaporation unit and condensing unit that is often configured without ducts
MMT	million metric tons
MMT CO_2e	million metric tons of carbon dioxide equivalent
MMTEVe	million metric tons of exchange value equivalent
MPC	manufacturer production cost
MSHP	mini-split heat pump
MT	metric tons
NPV	net present value
NREL	National Renewable Energy Laboratory
ODP	ozone depleting potential
ODS	ozone depleting substance
ORNL	Oak Ridge National Laboratory
PTAC	packaged terminal air conditioner
PTHP	packaged terminal heat pump
R-22	chlorodifluoromethane; common AC refrigerant prior to Montreal Protocol; HCFC refrigerant with global warming value of 1810; succeeded largely by HFC refrigerant R-410A
R-290	refrigerant name for propane, a hydrocarbon refrigerant; flammable and non-toxic refrigerant (class A3); GWP value of 3.3
R-32	difluoromethane; mildly flammable, non-toxic refrigerant blend (class A2L); GWP value of 675
R-410A	common variety of HFC refrigerant used for air conditioning equipment; mixture of difluoromethane (CH2F2, called R-32) and pentafluoroethane

Term	Definition
	(CHF2CF3, called R-125); GWP value of 2088; non-flammable and non-toxic refrigerant (class A1)
RAC	room air conditioner
RECS	Residential Energy Consumption Survey
SB	Senate Bill
SB 100	California Senate Bill 100, De León, Chapter 312, Statutes of 2018
SB 1383	California Senate Bill 1383, Lara, Chapter 395, Statutes of 2016
SB 1477	California Senate Bill 1477, Stern, Chapter 378, Statutes of 2018
SB 32	California Senate Bill 32, Pavley, Chapter 249, Statutes of 2016
SEER	seasonal energy efficiency rating
TIC	total installed cost
TMY3	typical meteorological year 3 (dataset from NREL)
TSD	technical support document
U.S. DOE	United States Department of Energy
U.S. EPA	United States Environmental Protection Agency
UEC	unit energy consumption
UL	Underwriters Laboratory
VRF	variable refrigerant flow
W	watt

References

Abdelaziz, O., S. Shrestha, J. Munk, R. Linkous, W. Goetzler, M. Guernsey, and T. Kassuga. 2015. *Alternative Refrigerant Evaluation for High-Ambient-Temperature Environments: R-22 and R-410A Alternatives for Mini-Split Air Conditioners*. Oak Ridge National Laboratory. ORNL/TM-2015/536. Available at https://www.energy.gov/sites/prod/files/2015/10/f27/bto_pub59157_101515.pdf.

ACR News. 2013. "R32 shows positive benefits in R410A drop-in test." *ACR News*, May 31, 2013. Available at https://www.acr-news.com/r32-shows-positive-benefits-in-r410A-drop-in-test.

AHRI (Air Conditioning, Heating, and Refrigeration Institute). 2015. *CAN/ANSI/AHRI 540-2015, Performance Rating of Positive Displacement Refrigerant Compressors and Compressor Units.* Air Conditioning, Heating, and Refrigeration Institute. Ottawa, Canada. Available at https://www.ahrinet.org/App_Content/ahri/files/STANDARDS/ANSI/CAN.ANSI.AHRI_Standard_540_E_2015.pdf.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). 2019. "ANSI/ASHRAE 34-2019, Designation and Safety Classification of Refrigerants." American Society of Heating, Refrigerating and Air-Conditioning Engineers. Available at https://www.ashrae.org/technical-resources/standards-and-guidelines/ashrae-refrigerant-designations.

Becker, L., P. Munzinger, and D. de Graaf. 2019. "R290 Split Air Conditioners Resource Guide - Version 1.0." Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Available at https://www.international-climate-initiative.com/fileadmin/Dokumente/2019/R290_SplitAC_ResourceGuide_Proklima.pdf.

Bitzer. 2020. *Refrigerant Report 21, A-501-21 EN.* Bitzer Kühlmaschinenbau GmbH. Available at https://www.bitzer-refrigerantreport.com/fileadmin/Content/01_Startseite/A-501-21_EN.pdf.

BRG Building Solutions. 2020. "The North American Commercial HVAC Product Markets – 2020 Edition." Available at https://www.brgbuildingsolutions.com/.

BSRIA Inc. (Building Services Research and Information Association, Incorporated). 2018. "Minisplits and VRF, USA Market Report." Available at https://www.bsria.com/uk/.

CARB (California Air Resources Board). 2017. *Potential Impact of the Kigali Amendment on California HFC Emissions Estimates and Methodology used to Model Potential Greenhouse Gas Emissions Reductions in California from the Global Hydrofluorocarbon (HFC) Phase-down Agreement of October 15, 2016, in Kigali, Rwanda ("Kigali Amendment")*. December 15, 2017. Written by the Research Division of the California Air Resources Board (CARB). Available at https://ww2.arb.ca.gov/sites/default/files/2018-12/CARB-Potential-Impact-of-the-Kigali-Amendment-on-HFC-Emissions-Final-Dec-15-2017.pdf.

CARB (California Air Resources Board). 2020a. "California Greenhouse Gas Emissions for 2000 to 2018." Available at https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2018/ghg_inventory_trends_00-18.pdf.

CARB (California Air Resources Board). 2020b. "Proposed Prohibitions on High-GWP HFCs in New Refrigeration and Air Conditioning." January 30, 2020. Available at https://ww2.arb.ca.gov/sites/default/files/2020-06/January%2030%2C%202020%20Workshop%20Slides.pdf.

CARB (California Air Resources Board). 2021. "High-Global Warming Potential (High-GWP) Refrigerants Include All Ozone-Depleting Substances and Any Refrigerant with a GWP of 150 or Higher." Available at https://ww2.arb.ca.gov/resources/documents/high-gwp-refrigerants.

Chrysalis Scientific. 2021. "Lower and Upper Explosive Limits for Flammable Gases and Vapors (LEL/UEL)." Available at https://www.chrysalisscientific.com/pg443-Lower-LEL-Upper-UEL-Explosive-Limits.pdf.

Colbourne D., I. C. Croiset, and L. Ederberg. 2011. "Cost Analysis Of ProducingSplit-Type Air Conditioners Using HC-290." Paper 629 Proceedings of the 23rd IIR International Congress of Refrigeration: Prague, Czech Republic, August 21-26, 2011.

Colbourne, D., B. Pätzold, and L. Meljac. 2020. "Quantitative Risk Assessment for Flammable Refrigerants, Public report for the project LIFE FRONT." June 2020. Available at http://lifefront.eu/wp-content/uploads/2020/06/life-front-risk-assessment-report-09062020_reduce.pdf.

Cooling Post. 2019. "R466A Passed by ASHRAE with A1 Classification." January 31, 2019. Available at https://www.coolingpost.com/world-news/r466a-passed-by-ashrae-with-a1-classification/.

Cooper, N. 2020. "Highly Rated Midea R290 Room AC Expected in Germany This Year." *Hydrocarbons21*, July 8, 2020. Available at https://hydrocarbons21.com/articles/9638/highly_rated_midea_r290_room_ac_expected_in_germany_this_year.

Coughlin, K., and B. Bereket. 2018. *Residential Electricity Prices: A Review of Data Sources and Estimation Methods.* Lawrence Berkeley National Laboratory. LBNL- 2001169. Available at https://eta.lbl.gov/publications/residential-electricity-prices-review.

Coughlin, K., and B. Bereket. 2019. *Non-residential Electricity Prices: A Review of Data Sources and Estimation Methods*. Lawrence Berkeley National Laboratory. LBNL-2001203. Available at https://eta.lbl.gov/publications/non-residential-electricity-prices.

EIA (Environmental Investigation Agency). 2021. "Briefing on the IEC Standards Proposal for Air-Conditioning." Environmental Investigation Agency. Available at https://eia-international.org/wp-content/uploads/EIA-Briefing-IEC-AC-Standards-Proposal.pdf.

EPS (Energy Performance Services). 2021. "Title 24 California Climate Zones 1-16." Energy Performance Services. Available at https://www.title24express.com/what-is-title-24/title-24-california-climate-zones/.

Figaro Engineering, Inc. 2020. Corporate Headquarters: Arlington Heights, IL. Price obtained for order of at least 100 gas sensor modules in May 2020. Gas Sensor Module: LPM2610-D09. Available at https://figarosensor.com/product/sensor/.

Fujitsu. 2021. "Service Manual, Split Type Room Air Conditioner Wall Mounted Type." Available at https://data2.manualslib.com/pdf4/100/9926/992575-fujitsu/asu9rlf1.pdf?6acdee9e43ee846e28a01d23083038cd.

Gao, Z., O. Abdelaziz, and T. L. LaClair. 2018. "Portable refrigerant charge meter and method for determining the actual refrigerant charge in HVAC systems." US9726410B2, issued August 2018. Available at https://patents.google.com/patent/US9726410B2/en?q=temperature+sensor&inventor=omar+abdelaziz%2c&oq=omar+abdelaziz%2c+temperature+sensor.

Gallagher, G. 2015. "ARB Research Division. ARB Methodology to Estimate GHG Emissions from ODS Substitutes." October 9, 2015.

Garry, M. 2020. "Initial Proposal on Higher Hydrocarbon Charge for ACs Passes." *Hydrocarbons21.* Available at https://hydrocarbons21.com/articles/9815/initial_proposal_on_higher_hydrocarbon_charge_for_acs_passes.

Goetzler, W., T. Sutherland, and C. Reis. 2013. *Energy Savings Potential and Opportunities for High-Efficiency Electric Motors in Residential and Commercial Equipment*. United States Department of Energy, Office of Energy Efficiency and Renewable Energy. Available at https://doi.org/10.2172/1220812.

Hine, T. 2021. 2021. "EPA Issues Proposed Rule for HFC Phasedown Under 2020 AIM Act." *Lexology*. May 25, 2021. Available at https://www.lexology.com/library/detail.aspx?g=d4fdc851-6f55-40b7-9e6c-5ffc636204c1.

Johnstone Supply Cooperative. 2020. Corporate Headquarters: Portland, OR. Prices obtained for the following parts in May 2020: Solenoid Valve Coil, Internal Product ID: 32837; Pressure Transducer, Internal Product ID: 3196K128; Thermocouple Wire, Internal Product ID: 38705K41. Available at https://www.johnstonesupply.com/.

IEC (International Electrotechnical Commission). 2021. "IEC 60079:2021 SER Series Explosive Atmospheres - ALL PARTS." International Electrotechnical Commission. Available at https://webstore.iec.ch/publication/62417.

LBNL (Lawrence Berkeley National Laboratory). 2021. "Testing Facilities." Lawrence Berkeley National Laboratory. Available at https://ees.lbl.gov/testing-capabilities.

Mahone, A., Z. Subin, G. Mantegna, R. Loken, C. Kolster, and N. Lintmeijer. 2020. *Achieving Carbon Neutrality in California, PATHWAYS Scenarios Developed for the California Air Resources Board Draft Report*. Energy and Environmental Economics, Inc.

McLaughlin, C. 2018. "Hydrocarbons Are on an Upward Trend Following Growth in 2017, According to Manufacturers." *Hydrocarbons21.* January 16, 2018. Available at http://hydrocarbons21.com/articles/8056/next_series_hydrocarbons_winning_light_commercial_race.

Midea. 2021. “MWEUK18CRN1MCK8 Midea 8,000 Btu 230/208-Volt Window Air Conditioner Replacement Parts.” Available at https://midea.encompass.com/model/MIDMWEUK18CRN1MCK8.

NREL (National Renewable Energy Laboratory). 2019. “Patent Protection Awarded to NREL’s EcoSnap-AC Technology.” National Renewable Energy Laboratory. Available at https://www.nrel.gov/news/program/2019/patent-protection-awarded-to-nrels-ecosnap-ac-technology.html.

NREL (National Renewable Energy Laboratory). 2021. “Typical Meteorological Year (TMY).” NSRDB: National Solar Radiation Database. Available at https://nsrdb.nrel.gov/data-sets/tmy.

PAE Engineers. 2020. *City of Seattle Refrigerant Emissions Analysis.* Available at https://www.seattle.gov/Documents/Departments/OSE/Building%20Energy/SEA_Refrigerant_Analysis_May2020.pdf.

Pallav, P., and L. Höglund-Isaksson. 2017. “Global emissions of fluorinated greenhouse gases 2005–2050 with abatement potentials and costs.” *Atmospheric Chemistry and Physics*, 17, 2795–2816. doi:10.5194/acp-17-2795-2017. Available at www.atmos-chem-phys.net/17/2795/2017/.

Payne, W. V., and P. A. Domanski. 2002. "A comparison of an R22 and an R-410A air conditioner operating at high ambient temperatures." July 1, 2002. *National Institute of Standards and Technology.* Available at https://www.nist.gov/publications/comparison-r22-and-r410a-air-conditioner-operating-high-ambient-temperatures-1.

Pham, H. M., and R. Rajendran. 2012. “R32 And HFOs As Low-GWP Refrigerants For Air Conditioning.” International Refrigeration And Air Conditioning Conference, 2012. Available at https://docs.lib.purdue.edu/iracc/1235/.

Refriparts. 2020. “Novo: Reator Condensadora Fujitsu Modelos Aobg Capacidades 09.000.” Price obtained in May 2020. Available at https://www.refriparts.com.br/pecas-de-ar-condicionado-split/transformador/reator-condensadora-fujitsu-modelos-aobg-capacidades-09000-ate-12000-btu.

RS Means. 2020. Installation Cost Data Book.

Shen, B., and B. Fricke. 2020. “Development of high efficiency window air conditioner using propane under limited charge.” *Applied Thermal Engineering*, 166, 114662. Available at https://doi.org/10.1016/j.applthermaleng.2019.114662.

Schultz, K. 2016. “Soft-Optimized System Test of R410A, DR-55, R32, and DR-5A in a 4-RT Unitary Rooftop Heat Pump.” AHRI Low GWP AREP Conference. Orlando, Florida, Jan. 21, 2016. Available at https://www.ahrinet.org/App_Content/ahri/files/RESEARCH/AREP_II/ACHP-III-2_Ingersoll_Rand.pdf.

Tsinghua, T. F. 2014. “Demonstration Project For HFC-32 Technology In The Manufacture Of Small-Sized Commercial Air-Source Chillers/Heat Pumps At Tsinghua Tong Fang Artificial Environment Co., Ltd.” United Nations Industrial Development Organization.

Turpin, J. R. 2020. "California Approves Rules To Phase Down HFCs." December 18, 2020. *The Air Conditioning, Heating, Refrigeration News.* Available at https://www.achrnews.com/articles/144212-california-approves-rules-to-phase-down-hfcs.

UL (Underwriters Laboratory). 2015. "Refrigerants and UL Standards." Regulations & Standards Session, 4th ATMOsphere America Conference. Atlanta, Georgia. June 2015.

UL (Underwriters Laboratory). 2019. "Standard for Household and Similar Electrical Appliances - Safety - Part 2-40: Particular Requirements for Electrical Heat Pumps, Air-Conditioners and Dehumidifiers 2019." Underwriters Laboratory. Available at https://standardscatalog.ul.com/ProductDetail.aspx?productId=UL60335-2-40.

UNEP (United Nations Environment Programme). 2019. "Project Proposals: Egypt." Executive Committee of the Multilateral Fund for Implementation of the Montreal Protocol. United Nations Environment Programme. Available at http://www.multilateralfund.org/84/English/1/8449.pdf.

UNDP (United Nations Development Programme). 2018 "Industrias Thermotar Ltda. - Demonstrative Project for HCFC-22 Phase Out in the Manufacturing of Commercial Air Conditioning Equipment." United Nations Development Programme.

UNIDO (United Nations Industrial Development Organization). 2014. "Demonstration Sub-Project for Conversion from HCFC-22 to Propane at Midea Room Air-conditioner Manufacturing Company; Demonstration Sub-Project for Conversion of Room A/C Compressor Manufacturing from HCFC-22 to Propane at Guangdong Meizhi Co." United Nations Industrial Development Organization. Available at http://multilateralfund.org/Our%20Work/DemonProject/Document%20Library/7317a1p3%20AC%20UNIDO.pdf.

U.S. Census Bureau. 2021. "State Population Totals and Components of Change: 2010-2019." Available at https://www.census.gov/data/tables/time-series/demo/popest/2010s-state-total.html.

U.S. CFR (United States Code of Federal Regulations). 2021a. "Title 10 - Appendix F to Subpart B of Part 430 - Uniform Test Method for Measuring the Energy Consumption of Room Air Conditioners." United States Code of Federal Regulations. Available at https://ecfr.io/Title-10/Part-430/Appendix-F#10:3.0.1.4.18.2.13.6.14.

U.S. CFR (United States Code of Federal Regulations). 2021b. "Title 10 - Appendix M to Subpart B of Part 430 - Uniform Test Method for Measuring the Energy Consumption of Central Air Conditioners and Heat Pumps." United States Code of Federal Regulations. Available at https://ecfr.io/Title-10/Part-430/Appendix-M#10:3.0.1.4.18.2.13.6.22.

U.S. CFR (United States Code of Federal Regulations). 2021c. "Title 10 – 431.96 Uniform test method for the measurement of energy efficiency of commercial air conditioners and heat pumps." United States Code of Federal Regulations. Available at https://ecfr.io/Title-10/Section-431.96.

U.S. DOE (United States Department of Energy). 2011. "Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment. Residential Clothes Dryers and Room Air Conditioners." Energy Efficiency and

Renewable Energy Office. April 25, 2011. Available at https://www.regulations.gov/document/EERE-2007-BT-STD-0010-0053.

U.S. DOE (United States Department of Energy). 2015a. "Technical Support Document. Energy Efficiency Program for Commercial and Industrial Equipment: Packaged Terminal Air Conditioners and Heat Pumps. Chapter 8 – Life-cycle-cost analysis." United States Department of Energy. Available at https://www.regulations.gov/document/EERE-2012-BT-STD-0029-0040.

U.S. DOE (United States Department of Energy). 2015b. "Direct Final Rule Technical Support Document: Energy Efficiency Program For Consumer Products And Commercial And Industrial Equipment: Small, Large, And Very Large Commercial Package Air Conditioning and Heating Equipment." 2015. United States Department of Energy. https://www.regulations.gov/document/EERE-2013-BT-STD-0007-0105.

U.S. DOE (United States Department of Energy). 2016. "Technical Support Document: Energy Efficiency Program for Consumer Products: Residential Central Air Conditioners and Heat Pumps." Energy Efficiency and Renewable Energy Office. Available at https://www.regulations.gov/document/EERE-2014-BT-STD-0048-0098.

U.S. DOE (United States Department of Energy). 2020a. "Room Air Conditioning National Impact Analysis Spreadsheets." United States Department of Energy. June 11, 2020.

U.S. DOE (United States Department of Energy). 2020b. "Technical Support Document: Energy Efficiency Program For Consumer Products And Commercial And Industrial Equipment: Room Air Conditioners." United States Department of Energy. Available at https://www.regulations.gov/docket/EERE-2014-BT-STD-0059/document.

U.S. DOE (United States Department of Energy). 2021. "Building Energy Codes Program, Prototype Building Models." United States Department of Energy. Available at https://www.energycodes.gov/prototype-building-models.

U.S. EIA (United States Energy and Information Administration). 2009. "2009 Residential Energy Consumption Survey (RECS)." United States Energy and Information Administration. Available at https://www.eia.gov/consumption/residential/data/2009/.

U.S. EIA (United States Energy and Information Administration). 2021. "Annual Energy Outlook 2021." United States Energy and Information Administration. Available at https://www.eia.gov/outlooks/aeo/.

U.S. EPA (United States Environmental Protection Agency). "Federal Register Vol. 80, No. 69 Part III, 40 CFR Part 82, [EPA–HQ–OAR–2013–0748; FRL–9922–26–OAR] RIN 2060–AS04 Protection of Stratospheric Ozone: Listing of Substitutes for Refrigeration and Air Conditioning and Revision of the Venting Prohibition for Certain Refrigerant Substitutes." April 10, 2015. United States Environmental Protection Agency.

U.S. EPA (United States Environmental Protection Agency). 2021. "Proposed Rule - Phasedown of Hydrofluorocarbons: Establishing the Allowance Allocation and Trading Program under the AIM Act." May 19, 2021. United States Environmental Protection Agency. Available at https://www.regulations.gov/document/EERE-2014-BT-STD-0059-0011.

Wan, H., T. Cao, Y. Hwang, R. Radermacher, and S. Chin. 2021. "Comprehensive investigations on Life Cycle Climate Performance of Unitary Air-Conditioners." *International Journal of Refrigeration*, 129, 332-341. ISSN 0140-7007. Available at https://doi.org/10.1016/j.ijrefrig.2021.04.033.

Wang, X., and K. Amrane. 2014. "AHRI Low Global Warming Potential Alternative Refrigerants Evaluation Program (Low-GWP AREP) Summary of Phase I Testing Results." 15th International Refrigeration and Air Conditioning Conference at Purdue.

Wang, X., and K. Amrane. 2016. "AHRI Low Global Warming Potential Alternative Refrigerants Evaluation Program (Low-GWP AREP) Summary of Phase II Testing Results." International Refrigeration and Air Conditioning Conference. Paper 1586. Available at http://docs.lib.purdue.edu/iracc/1586.

Younits. 2020. "Fujitsu K9709907078 Main Board PCB." Price obtained in May 2020. Available at https://younits.com/k9709907078.html.

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Appendix A: Modeling Results

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APPENDIX A: Modeling Results

Table A-1: Optimal Design of Model #1 (R-290 Window Unit)

	Baseline R-22	R-290 drop-in	R-290 Optimal
Indoor Unit			
Tube length[m/in]	0.267/10.5	0.267/10.5	0.32/12.6
FPI	19	19	22
Fan Power* [W]	73	73	58
Vertical spacing [m/in]	0.035/1.389	0.035/1.389	0.028/1.10
Horizontal spacing [m/in]	0.019/0.75	0.019/0.75	0.015/0.60
Outdoor Unit			
Tube length[m/in]	0.502/19.75	0.502/19.75	0.55/21.65
FPI	19	19	21.5
Fan Power* [W]	109.5	109.5	87
Vertical spacing [m/in]	0.028/1.1125	0.028/1.1125	0.024/0.94
Horizontal spacing [m/in]	0.013/0.5	0.013/0.5	0.014/0.55
Net Air-side Capacity [W]	1962.878	1848.766 (-5.8%)↓	1913.657 (-2.5%) ↓
Power [W]	772.652	651.344 (-15.7%) ↓	607.074 (-21.4%)↓
EER [W/W]	2.54	2.84 (11.8%)↑	3.152 (24.1%)↑

*Fan power is not an optimization design variable. A 20 percent energy saving is assumed in this report to consider the replacement of fan motors from AC to DC.
Source: Authors' calculations

Table A-2: Optimal Design of Model #2 (R-290 Mini-Split Unit)

	Baseline R-22	R-290 drop-in	R-290 Optimal
Indoor Unit			
Tube length[m/in]	0.63/24.75	0.63/24.75	0.6/23.62
FPI	18	18	21.4
Fan Power* [W]	36.5	36.5	29.2
Vertical spacing [m/in]	0.022/0.875	0.022/0.875	0.027/1.063
Horizontal spacing [m/in]	0.013/0.5	0.013/0.5	0.011/0.433

	Baseline R-22	R-290 drop-in	R-290 Optimal
Outdoor Unit			
Tube length[m/in]	0.737/29.0	0.737/29.0	0.86/33.86
FPI	18.5	18.5	22.5
Fan Power* [W]	45	45	36
Vertical spacing [m/in]	0.025/1.0	0.025/1.0	0.024/0.945
Horizontal spacing [m/in]	0.022/0.875	0.022/0.875	0.017/0.669
Net Air-side Capacity [W]	2404.125	2293.245 (-4.6%)↓	2395.358 (-0.4%) ↓
Power [W]	706.687	622.177 (-12.0%) ↓	608.198 (-13.9%)↓
System: COP	3.402	3.686 (8.3%)↑	3.938 (15.8%)↑

*Fan power is not an optimization design variable. A 20 percent energy saving is assumed in this report to consider the replacement of fan motors from AC to DC.
Source: Authors' calculations

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Appendix B: R-290 Charge Optimization Test Results

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APPENDIX B:
R-290 Charge Optimization Test Results

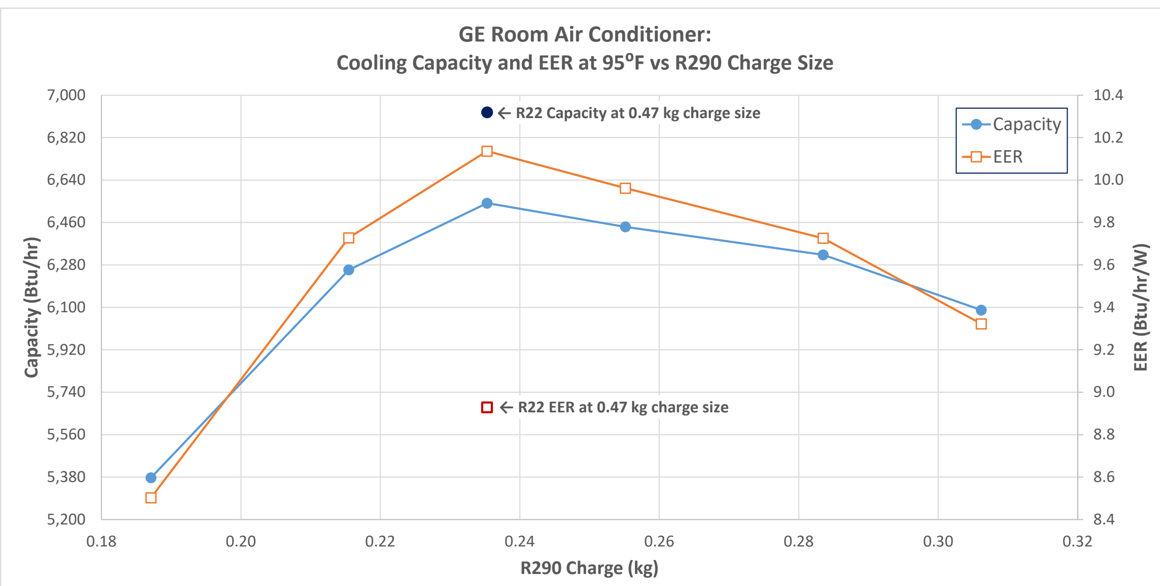
Appendix B details the testing performed on six R-22 air conditioners consisting of two window air conditioners, two mini-split air conditioners, and two packaged terminal air conditioners. Testing was performed in accordance with U.S. DOE test procedures. The six air conditioners were tested at their nameplate R-22 charge levels to establish their baseline cooling capacity and energy efficiency at the U.S. DOE "A" test condition (specifically indoor temperature of 80°F [26.67°C] dry-bulb / 67°F [19.44°C] wet-bulb and outdoor temperature of 95°F [35°C] dry-bulb). Drop-in testing with R-290 was then conducted at various charge levels to determine the optimized R-290 level that maximized energy efficiency.

Window Air Conditioners

General Electric Room Air Conditioner, Model AGM08FDM1

This window air conditioner was tested over a range of R-290 charge levels spanning 40 percent to 65 percent of the baseline R-22 charge level. The optimized R-290 charge level was 50 percent of the R-22 baseline level or 0.235 kg. Figure B-1 shows the cooling capacity and efficiency results over the range of R-290 charge levels tested.

Figure B-1: R-290 Charge Optimization Test Results for the General Electric Window Air Conditioner



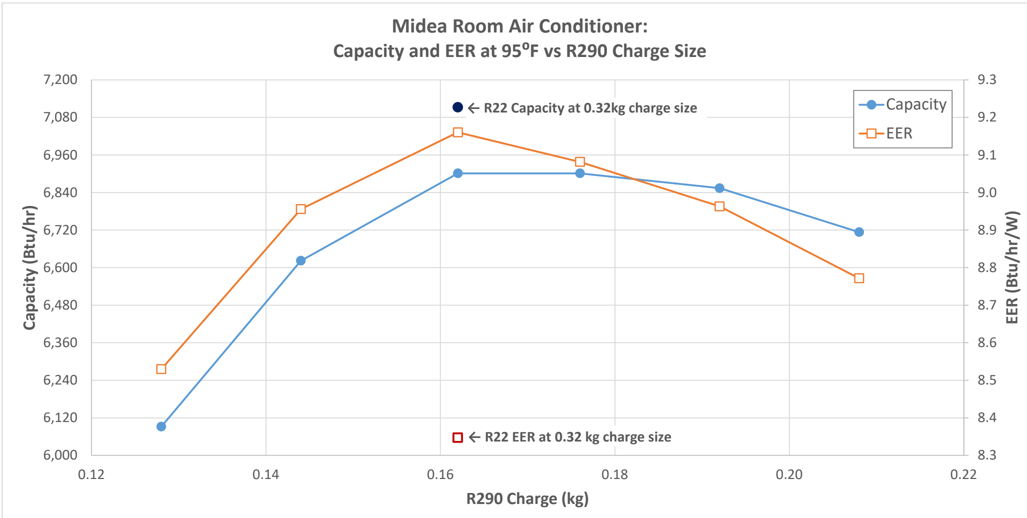
Source: Authors' testing

Midea Window Air Conditioner, Prototype

This window air conditioner was tested over a range of R-290 charge levels spanning 40 percent to 65 percent of the baseline R-22 charge level. The optimized R-290 charge level was

50 percent of the R-22 baseline level or 0.16 kg. Figure B-2 shows the cooling capacity and efficiency results over the range of R-290 charge levels tested.

Figure B-2: R-290 Charge Optimization Test Results for the Midea Window Air Conditioner



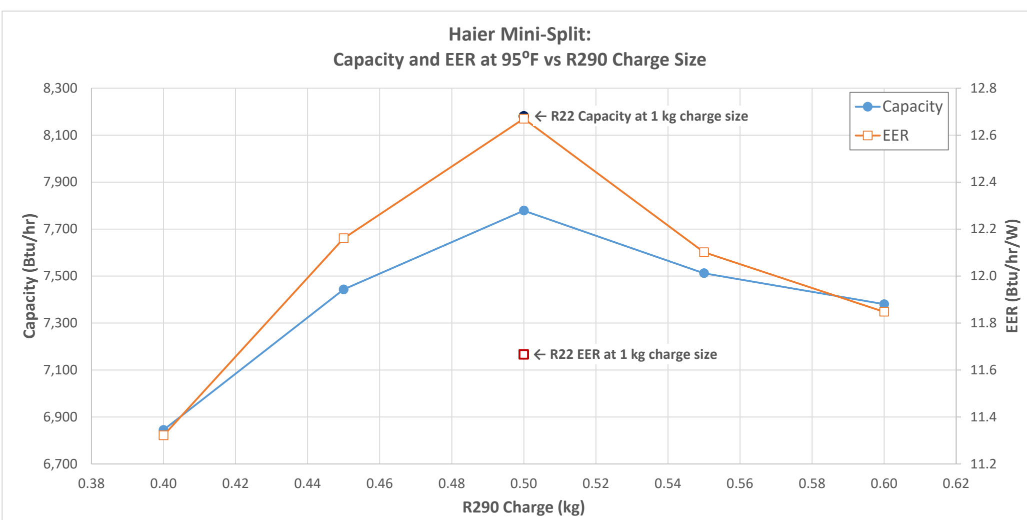
Source: Authors' testing

Mini-Split Air Conditioners

Haier Mini-Split Air Conditioner, Model KFR-23W2012

This mini-split air conditioner was tested over a range of R-290 charge levels spanning 40 percent to 60 percent of the baseline R-22 charge level. The optimized R-290 charge level was 50 percent of the R-22 baseline level or 0.50 kg. Figure B-3 shows the cooling capacity and efficiency results over the range of R-290 charge levels tested.

Figure B-3: R-290 Charge Optimization Test Results for the Haier Mini-Split Air Conditioner



Source: Authors' testing

Because mini-split air conditioners are considered to be central air conditioners in the U.S., the mini-split was also tested at the U.S. DOE "B" test condition (specifically indoor temperature of 80°F [26.67°C] dry-bulb / 67°F [19.44°C] wet-bulb and outdoor temperature of 82°F [27.78°C] dry-bulb). Table B-1 shows the cooling capacity, power consumption, and energy efficiency at the R-22 baseline and the R-290 optimized charge levels.

Table B-1: Haier Mini-Split Air Conditioner Test Results at U.S. DOE "B" Test Condition

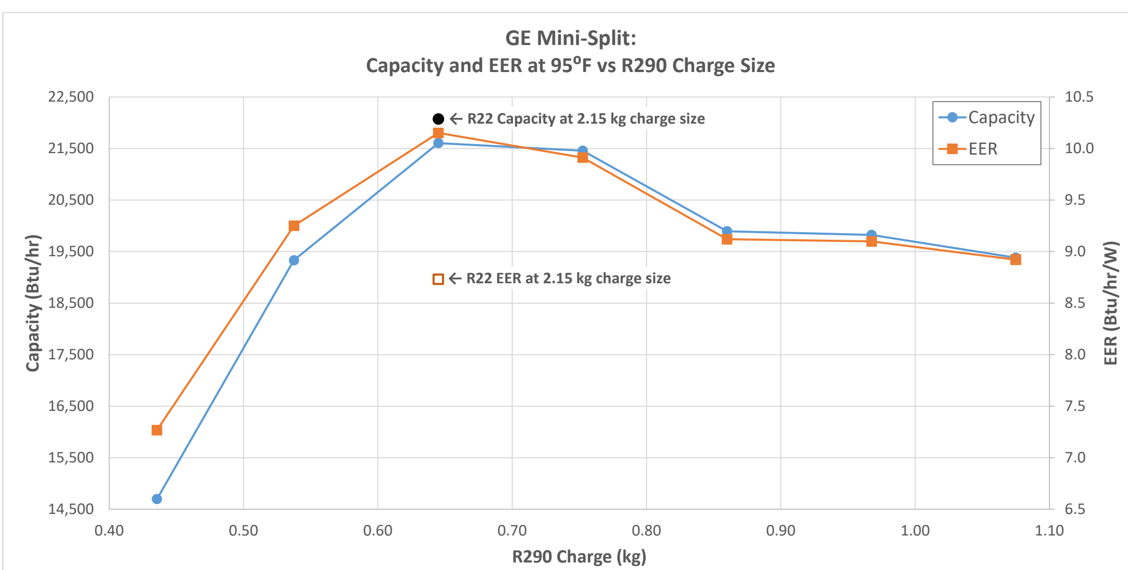
	R-22 Baseline Level	R-290 Optimized Level	R-290 impact relative to R-22
Cooling Capacity (Btu/hr)	7,944	8,226	+4%
Power (W)	619	540	-13%
EER (Btu/hr/W)	12.8	15.2	+19%

Source: Authors' testing

General Electric Mini-Split Air Conditioner, Model GESFBH24OUAA

For the General Electric mini-split air conditioner, because an R-22 indoor unit was unavailable, an R-410A indoor unit was paired with the R-22 outdoor condensing unit. This mini-split air conditioner was tested over a range of R-290 charge levels spanning 20 percent to 50 percent of the baseline R-22 charge level. The optimized R-290 charge level was 30 percent of the R-22 baseline level or 0.645 kg. Because the General Electric mini-split air conditioner consisted of an R-22 outdoor condensing unit and an R-410A indoor unit, the R-290 optimized charge level was far below the R-22 baseline level. Figure B-4 shows the cooling capacity and efficiency results over the range of R-290 charge levels tested.

Figure B-4: R-290 Charge Optimization Test Results for the General Electric Mini-Split Air Conditioner



Source: Authors' testing

Because mini-split air conditioners are considered to be central air conditioners in the U.S., the mini-split was also tested at the U.S. DOE "B" test condition (specifically indoor temperature of 80°F [26.67°C] dry-bulb / 67°F [19.44°C] wet-bulb and outdoor temperature of 82°F [27.78°C] dry-bulb). Table B-2 shows the cooling capacity, power consumption, and energy efficiency at the R-22 baseline and the R-290 optimized charge levels.

Table B-2: Haier Mini-Split Air Conditioner Test Results at U.S. DOE "B" Test Condition

	R-22 Baseline Level	R-290 Optimized Level	R-290 impact relative to R-22
Cooling Capacity (Btu/hr)	23,580	23,217	-2%
Power (W)	2,257	1,917	-15%
EER (Btu/hr/W)	10.4	12.1	+16%

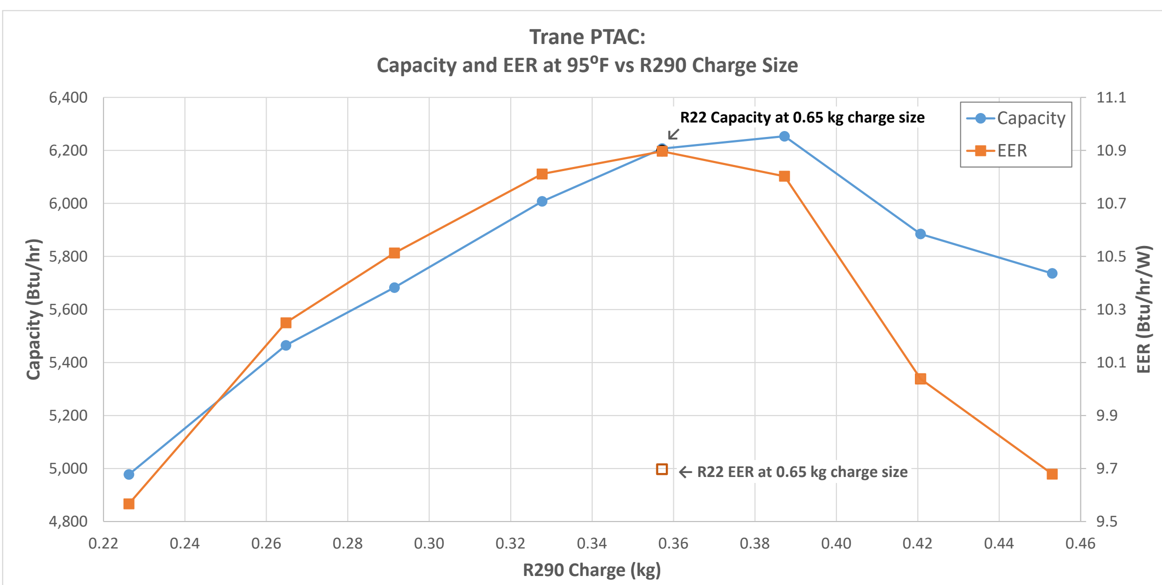
Source: Authors' testing

Packaged Terminal Air Conditioners

Trane Packaged Terminal Air Conditioner, Model PTED0702GCA

This PTAC was tested over a range of R-290 charge levels spanning 35 percent to 70 percent of the baseline R-22 charge level. The optimized R-290 charge level was 55 percent of the R-22 baseline level or 0.36 kg. Figure B-5 shows the cooling capacity and efficiency results over the range of R-290 charge levels tested.

Figure B-5: R-290 Charge Optimization Test Results for the Trane PTAC

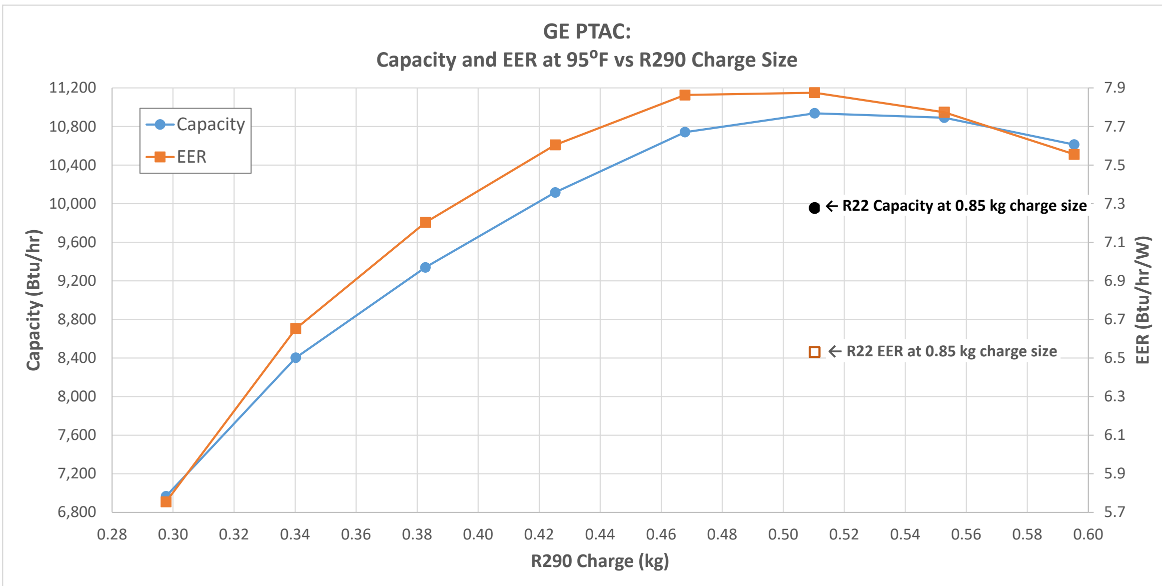


Source: Authors' testing

General Electric Packaged Terminal Air Conditioner, Model AZ38H15DADM1

This PTAC was tested over a range of R-290 charge levels spanning 35 percent to 70 percent of the baseline R-22 charge level. The optimized R-290 charge level was 60 percent of the R-22 baseline level or 0.51 kg. Figure B-6 shows the cooling capacity and efficiency results over the range of R-290 charge levels tested.

Figure B-6: R-290 Charge Optimization Test Results for the General Electric PTAC



Source: Authors' testing

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Appendix C: Cost of R-290 Equipment Analyses

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APPENDIX C:
Cost of R-290 Equipment Analyses

This appendix details the cost analyses performed for establishing the increased cost of manufacturing and installation R-290 air conditioners.

Additional Cost Approach for R-290 From R-32

The additional manufacture and installation costs of air conditioning equipment using R-290 as a refrigerant compared to R-32 was done in a piecewise fashion. In addition to the analysis above for R-410A to R-290 conversion costs, incremental equipment costs were obtained from the literature for upgrading from R-410A to R-32. The net cost of upgrading from R-32 to R-290 was then approximated as the upgrade costs from R-410A to R-32 subtracted from those from upgrading from R-410A to R-290.

Upgrade costs (R-32 to R-290) ≈ Upgrade costs (R-410A to R-290) – Upgrade costs (R-410A to R-32)

Since R-32 is mildly flammable, it incurs some upgrade costs from non-flammable R-410A, and the costs of upgrading from mildly flammable R-32 to flammable R-290 should be lower than those from non-flammable R-410A to R-290 as reflected in the equation above.

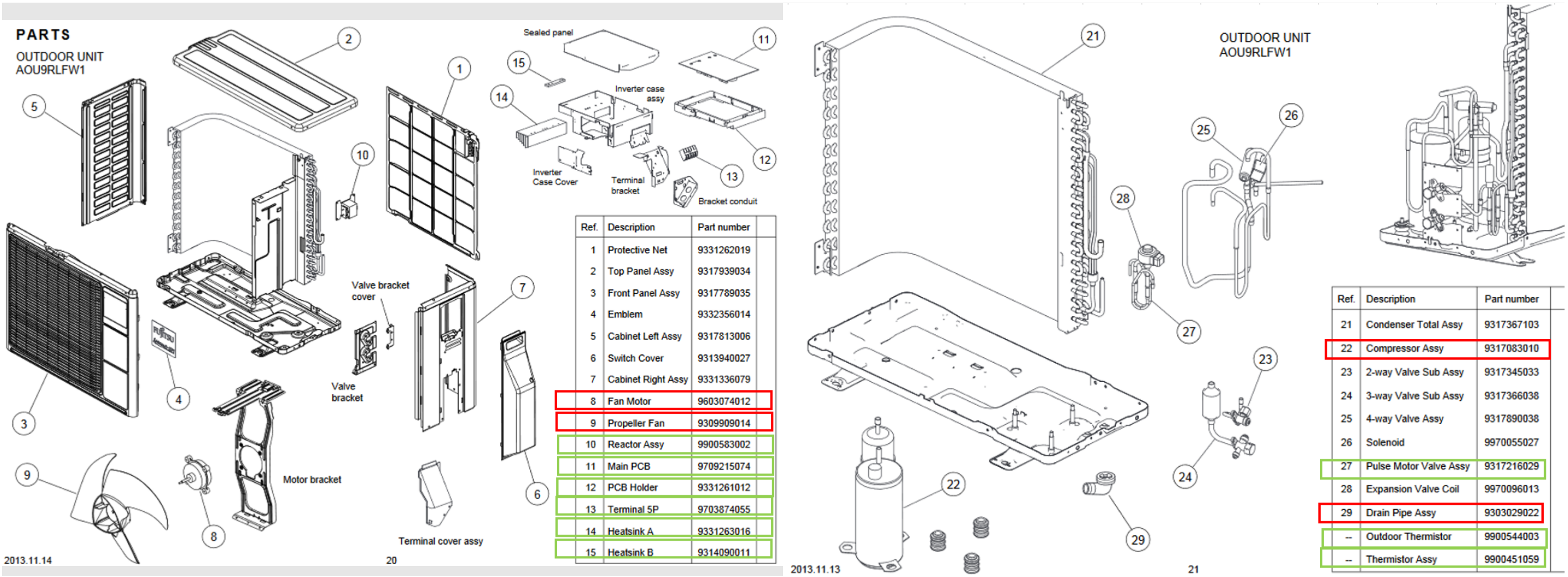
Existing Parts Analysis for R-290 from R-410A

An "existing parts" analysis was conducted to identify the existing parts in an air conditioner that need to be replaced to prevent potential sources of ignition if a refrigerant leak occurs when using an A3 refrigerant such as R-290. Bill of materials (BOM) for two air conditioners were obtained for two air conditioners: (1) a Fujitsu mini-split air conditioner (model ASU9RLF1 and AOU9RLFW1) and a Midea window air conditioner (model MWEUK18CRN1MCK8). Supplier prices were obtained on most components in the BOMs. It was then determined whether any components needed to be replaced in order to prevent sources of ignition.

Fujitsu Mini-Split Air Conditioner BOM and Supplier Prices

Figure C-1 and Figure C-2 show the BOMs for the outdoor and indoor units of the Fujitsu mini-split air conditioner. In the figure below, the parts outlined in green are considered for replacement because they constitute the control circuitry. Parts outlined in red are considered for replacement because they either contain a motor or sensitive metal parts.

Figure C-1: Fujitsu Mini-Split Air Conditioner Outdoor Unit BOM

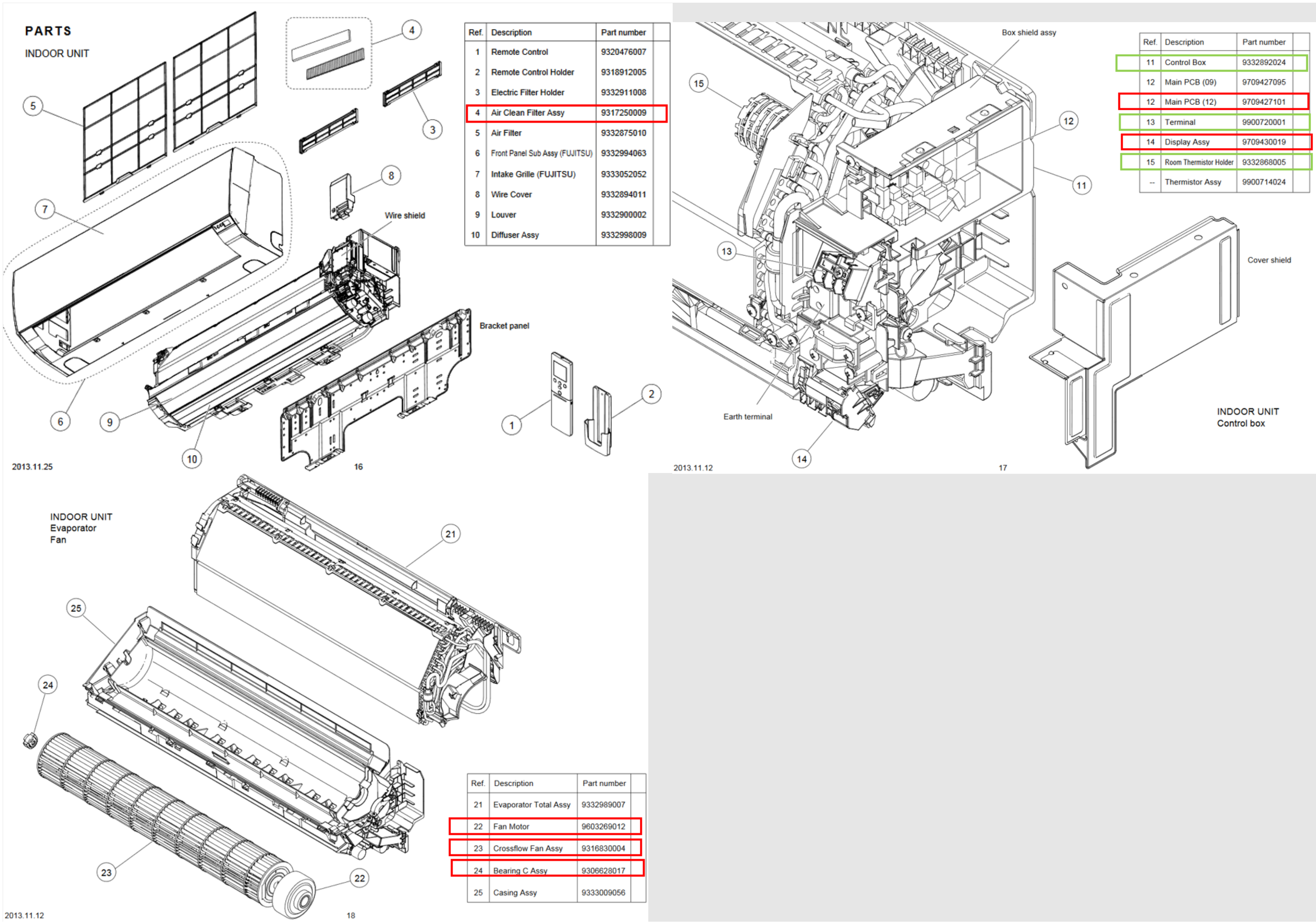


Ref.	Description	Part number
1	Protective Net	9331262019
2	Top Panel Assy	9317939034
3	Front Panel Assy	9317789035
4	Emblem	9332356014
5	Cabinet Left Assy	9317813006
6	Switch Cover	9313940027
7	Cabinet Right Assy	9331336079
8	Fan Motor	9603074012
9	Propeller Fan	9309909014
10	Reactor Assy	9900583002
11	Main PCB	9709215074
12	PCB Holder	9331261012
13	Terminal 5P	9703874055
14	Heatsink A	9331263016
15	Heatsink B	9314090011

Ref.	Description	Part number
21	Condenser Total Assy	9317367103
22	Compressor Assy	9317083010
23	2-way Valve Sub Assy	9317345033
24	3-way Valve Sub Assy	9317366038
25	4-way Valve Assy	9317890038
26	Solenoid	9970055027
27	Pulse Motor Valve Assy	9317216029
28	Expansion Valve Coil	9970096013
29	Drain Pipe Assy	9303029022
--	Outdoor Thermistor	9900544003
--	Thermistor Assy	9900451059

Source: Fujitsu 2021

Figure C-2: Fujitsu Mini-Split Air Conditioner Indoor Unit BOM



Ref.	Description	Part number	
1	Remote Control	9320476007	
2	Remote Control Holder	9318912005	
3	Electric Filter Holder	9332911008	
4	Air Clean Filter Assy	9317250009	
5	Air Filter	9332875010	
6	Front Panel Sub Assy (FUJITSU)	9332994063	
7	Intake Grille (FUJITSU)	9333052052	
8	Wire Cover	9332894011	
9	Louver	9332900002	
10	Diffuser Assy	9332998009	

Ref.	Description	Part number	
11	Control Box	9332892024	
12	Main PCB (09)	9709427095	
12	Main PCB (12)	9709427101	
13	Terminal	9900720001	
14	Display Assy	9709430019	
15	Room Thermistor Holder	9332868005	
--	Thermistor Assy	9900714024	

Ref.	Description	Part number	
21	Evaporator Total Assy	9332989007	
22	Fan Motor	9603269012	
23	Crossflow Fan Assy	9316830004	
24	Bearing C Assy	9306628017	
25	Casing Assy	9333009056	

Source: Fujitsu 2021

Table C-1 provides the supplier obtained prices for the critical components in the outdoor and indoor unit BOMs. Supplier prices for almost all the components were obtained from Johnstone Supply, a supplier of replacement and repair parts and maintenance supplies for heating, ventilation, air conditioning, and refrigeration (HVACR) equipment (Johnstone Supply Cooperative, 2020). Prices for the reactor assembly and main primary control board were obtained from Refriparts and Younits, respectively (Refriparts, 2020; Younits, 2020). The total supplier price of the components is $1,977.

Table C-1: Fujitsu Mini-Split Air Conditioner Outdoor and Indoor Unit Component Suppler Prices

Outdoor Unit			Indoor Unit		
Ref. No.	**Part Description**	**Supplier Price**	**Ref. No.**	**Part Description**	**Supplier Price**
8	Fan Motor	$72.50	4	Air clean filter	$44.50
9	Fan Blade	$39.50	12	Main PCB	$84.50
10	Reactor Assy	$308.00	13	Terminal	$2.40
11	Main PCB	$617.85	14	Display Assy	$23
13	Terminal 5p	$2.49	15	Room Thermistor	$11.75
14	Heatsink	$6.95	22	Fan Motor	$63.08
15	Heatsink	$23.61	23	Crossflow Fan Assy	$35.06
22	Compressor	$442.50	24	Bearing C Assy	$9.14
27	Expansion Valve	$130.40	Total Indoor Unit Price		$273.11
28	Expansion Valve Coil	$47.50			
29	Drain Pipe Assy	$6.00			
--	Outdoor Thermistor	$7.00			
Total Outdoor Unit Price		$1704.30			
Total Outdoor and Indoor Purch. Parts					**$1729**

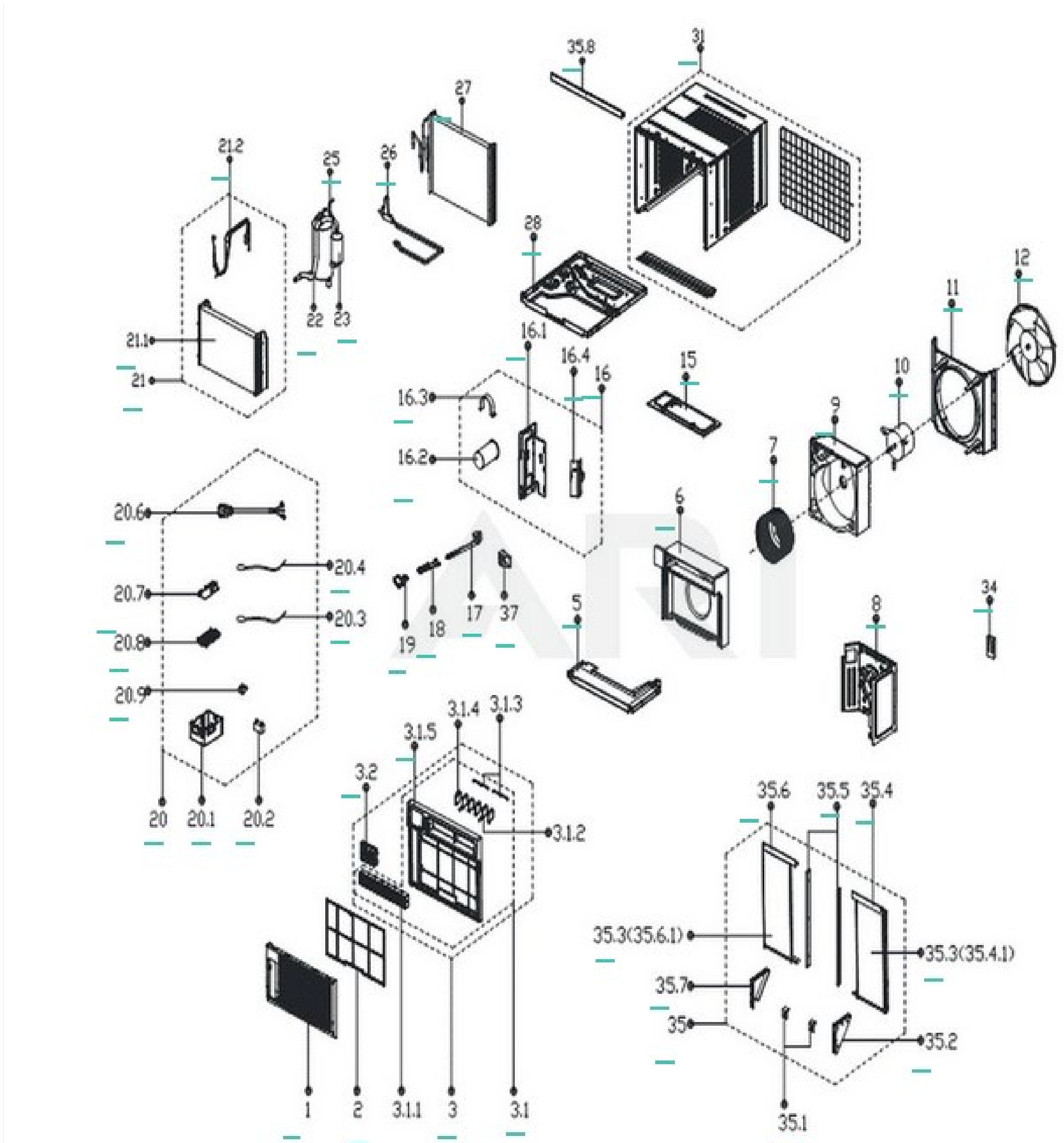
Source: Authors' calculations

Of the critical components identified and priced in the Fujitsu mini-split air conditioner, none were determined to need replacement, with the exception of the compressor which is treated separately. Fan blades and housing are already plastic, circuit boards and housing are already solid-state and plastic, and motors were determined to be direct current. Therefore, no additional cost would need to be incurred by in the Fujitsu mini-split air conditioner to have it safely use R-290.

Midea Window Air Conditioner BOM and Supplier Prices

Figure C-3 shows the BOM for the Midea room air conditioner.

Figure C-3: Midea Room Conditioner Outdoor Unit BOM



Source:

Table C-2 provides the supplier obtained prices for the all the in the window air conditioner BOM. Supplier prices were obtained from Midea (Midea, 2021). A price for each component is made available by Midea directly through their website. The total supplier price of the components is $886.

Table C-2: Midea Window Air Conditioner Component Suppler Prices

Ref. No.	Part Description	Supplier Price	Ref. No.	Part Description	Supplier Price
1	Panel	$27.95	20.4	Sensor (Ambient Temp)*	$5.95
2	Air Filter*	$15.95	20.6	Power Cord*	$60.95
3	Panel Frame Assy	--	20.7	Main Control Board*	$47.95
3.1	Panel Frame Assy	$27.95	20.8	Bracket of MCB*	$10.95
3.1.5	Panel Frame	$42.95	20.9	Transformer*	$21.95
3.2	Display Box*	$51.95	21	Evap Assy	--
5	Drain Pan	$20.95	21.1	Evaporator	$131.95
6	Foam, Air Outlet	$28.95	21.2	Capillary Assy*	$35.95
7	Blower Wheel/Centrifugal fan	$29.95	22	Suction pipe Assy	$40.95
8	Front Barrier Board	$59.95	23	Compressor*	$275.95
9	Rear Volute Shell	$36.95	25	Discharge Pipe Assy	$29.95
10	Fan Motor*	$137.95	26	Cooling coil Assy	$64.95
11	Rear Seperation	$53.95	27	Condesnor Assembly	$154.95
12	Axial Flow Fan*	$43.95	28	Chassis Assembly	$54.95
15	Front Cover	$21.95	31	Cabinet Assembly	$78.95
16	Midea part	$0.95	34	Remote Controller*	$32.95
16.1	Front Left Barrier Board Subassy	$27.95	35	Installation Accessory	$42.95
16.2	Capacitor*	$27.95	35.1	Installing Located Block	$5.95
16.3	Capacitor Clip	$3.95	35.2	Right Bracket	$10.95
16.4	Capacitor*	$10.95	35.3	Shutter	$13.95
17	Fresh Air Door	$5.95	35.4	Window Accordian Subassy	$32.95
18	Bracket	$5.95	35.5	Connecting Rod	$10.95
19	Connecting Rod	$4.95	35.6	Window Accordian Subassy	$32.95
20	Electronic Box Control Assy	--	35.7	Left Bracket	$10.95
20.1	Electronic Control Box*	$20.95	35.8	Shutter Framt (Upper)	$20.95
20.2	Capacitor (Fan Motor)*	$20.95	37	Bracket (Fresh Air)	$5.95
20.3	Sensor (Pipe Temp)*	$10.95			
				Total Purch. Parts	**$886.10**

*Specifies components considered for replacement.
Source: Authors' estimates

Of the critical components identified and priced in the Midea air conditioner, none were determined to need replacement with the exception of the compressor which is treated separately. Fan blades and housing are already plastic, circuit boards and housing are already solid-state and plastic, and motors were determined to be direct current. No additional cost would need to be incurred by in the Midea window air conditioner to have it safely use R-290.

Additional Parts Analysis for R-290 From R-410A

An "additional parts" analysis was conducted to identify the additional parts for an R-290 air conditioner that need to be added for refrigerant leak detection and unit shut down. For a primary safety system, gas detection sensors to detect refrigerant leaks and solenoid values to prevent refrigerant migration are required. For a redundant safety system, temperature and pressure sensors are required. Table C-3 shows the additional components required for the primary and redundant safety systems and their corresponding supplier prices. Also included are the number of additional components required for the Fujitsu mini-split air conditioner and the Midea window air conditioner. The total supplier prices of the additional components for both air conditioners are included in Table 37. Supper prices were obtained from Figaro Engineering, Inc. (Figaro Engineering, 2020). Supplier prices for the solenoid, thermocouple wire, and pressure transducer were obtained from Johnstone Supply (Johnstone Supply Cooperative, 2020).

Table C-3: R-290 Safety System Prices

Safety System		Fujitsu Mini-Split AC		Midea Room AC	
Components	**Supplier Price**	**Number**	**Price**	**Number**	**Price**
Primary System					
Leak Detection Sensors	$6.23	4	$24.90	1	$6.23
Solenoids	$57.50	2	$30.15	1	$30.15
Primary Safety System Price			$55.05		$36.37
Redundant System					
Thermocouple Wire	$1.04 per foot	4 feet	$8.32	2 feet	$4.16
Pressure Transducers	$40.62	2	$81.24	1	$40.62
Redundant Safety System Price			$89.56		$44.78
Primary + Redundant System Price			$144.61		$81.15

Source: Authors' estimates

Relative to the BOM prices of the Fujitsu mini-split air conditioner ($1,729) and the Midea window air conditioner ($886), the R-290 primary safety system prices represent a 3 percent and 4 percent increase, respectively. The combined R-290 primary and redundant safety system prices represent increases of 8 percent and 9 percent for the Fujitsu 2-ton and Midea 1.5-ton air conditioners, respectively.

Additional Cost of Mini-split and Window AC for R-290 From R-32

A lower incremental cost is expected for R-290 units compared to a reference case of R-32 versus the case of R-290 units compared to a reference case of R-410A. As described the following approximate relationship to estimate upgrade costs of R-32 units to R-290 was used:

Upgrade costs (R-32 to R-290) ≈ Upgrade costs (R-410A to R-290) – Upgrade costs (R-410A to R-32)

For the upgrade costs of R-410A to R-290 the earlier results from this report were used. For the upgrade costs of R-410A to R-32 the results of two reports were used: (1) UNEP 2019 Project proposal for HCFC-22 to HFC-32 (UNEP 2019); and (2) a Demonstration project for HFC-32 technology [from HCFC-22] in the manufacture of small-sized commercial air-source chillers/heat pumps in China (Tsinghua Tong Fang 2014). The small difference in charge between HCFC-22 and R-410A was accounted, but otherwise assume that the upgrade costs from non-flammable R-410A to R-32 is very similar to that for non-flammable HCFC-22 (R-22) to R-32. The team found that the upgrade cost from R-410A to R-32 is $12.97 for the 2-ton mini-split, and about $7.33 for the window AC (Tables C-4 and C-5). Subtracting this from the upgrade costs for R-410A to R-290 gives an average 1.3 percent increase in cost for the mini-split and 3.7 percent increase in cost for the window AC for R-32 to R-290. This is about one-half of the upgrade costs estimated in this report for R-410A to R-290.

Table C-4: R-290 Fujitsu Mini-Split Air Conditioner Manufacturer Product Cost Increase from R-32

	2-ton Central Air Conditioner MPCs*							Adjusted MPCs for R-290 Fujitsu Mini-Split	CORRECTION for R-410-A to R-32 addititional cost			
	Materials											
SEER	Total	Purch. Parts Frac.**	Labor	Overhead	Deprecia-tion	Total MPC	R-290 Safety: Purch. Parts Increase	MPC incremental cost	Incremental cost for R-32 from R-410A***	MPC incremental cost R-32 to R-290	Adj. MPC assuming R-32 reference	Percent inc. in MPC for R-290 assuming R-32 reference
Primary Safety System												
14	$520	$276	$81	$15	$32	$648	3%	$10.47	$12.97	-$2.51	$645	-0.4%
21	$1,168	$619	$117	$19	$59	$1,362	-	$10.47	$12.97	-$2.51	$1,359	-0.2%
Primary and Redundant Safety Systems												
14	$520	$276	$81	$15	$32	$648	8%	$24.77	$12.97	$11.79	$660	1.8%
21	$1,168	$619	$117	$19	$59	$1,362	-	$24.77	$12.97	$11.79	$1,374	0.9%
											avg	1.3%

* Source: U.S. DOE TSD, Residential Clothes Dryers and Room Air Conditioners, Direct Final Rule. Chapter 12, Section 12.4.6.2. April 2011, Author calculations
** Purchased Parts Fraction is 53 percent of total Materials Cost. Source: U.S. DOE TSD, Residential Clothes Dryers and Room Air Conditioners, Direct Final Rule. Chapter 5, Section 5.6.2.3. April 2011.
*** Source: R-32 Egypt report (UNEP, 2019) and R-32 China Conversion report (Tsinghua, 2014)

Table C-5: R-290 Midea Room Air Conditioner Manufacturer Product Cost Increase from R-32

	Window Air Conditioner MPCs*							Adjusted MPCs for R-290 Midea Window AC	CORRECTION for R-410A to R-32 additional cost			
	Materials											
Cooling Capacity (kBtu/h)	Total	Purch. Parts Frac.**	Labor	Overhead	Depreciation	Total MPC	R-290 Safety: Purch. Parts Increase	MPC incremental cost	Incremental cost for R-32 from R-410A***	MPC incremental cost R-32 to R-290	Adj. MPC assuming R-32 reference	Percent inc. in MPC for R-290 assuming R-32 reference
Primary Safety System												
<6	$116	$62	$24	$24	$7	$173	-	$11.15	$7.33	$3.82	$177	2.2%
8-13.9	$149	$79	$31	$20	$9	$209	-	$9.60	$7.33	$2.27	$211	1.1%
20-24.9	$277	$147	$43	$27	$16	$363	4%	$6.51	$7.33	-$0.83	$362	-0.2%
Primary and Redundant Safety Systems												
<6	$116	$62	$24	$24	$7	$173	-	$17.09	$7.33	$9.76	$183	5.6%
8-13.9	$149	$79	$31	$20	$9	$209	-	$15.55	$7.33	$8.21	$217	3.9%
20-24.9	$277	$147	$43	$27	$16	$363	9%	$12.45	$7.33	$5.12	$368	1.4%
											avg	3.7%

* Source: U.S. DOE TSD, Residential Clothes Dryers and Room Air Conditioners, Direct Final Rule. Chapter 12, Section 12.4.6.2. April 2011, Author calculations.
** Purchased Parts Fraction is 53 percent of total Materials Cost. Source: U.S. DOE TSD, Residential Clothes Dryers and Room Air Conditioners, Direct Final Rule. Chapter 5, Section 5.6.2.3. April 2011.
*** Source: R-32 Egypt report and R-32 China Conversion report (Tsinghua, 2014)

Installation Cost Analysis

Additional installation measures to ensure the safe installation of R-290 air conditioners impact the amount of time required to install them. But because both window air conditioners and PTACs are factory charged, it is assumed no additional installation time is required for these air conditioner types. Only mini-split air conditioners are charged in the field and would incur additional installation time.

Because HVAC technicians should be familiar with current installation practices, such as those that would be required for the handling of A3 refrigerants, it is assumed that no more than an hour over current installation times would be required to install air conditioning equipment charged with R-290. Data from RS Means provides the increased installation for an additional hour of technician time (RS Means, 2020). Table C-6 summarizes the hourly rates for an HVAC installation crew for commercial and residential sectors, which are $177 and $124, respectively.

Table C-6: U.S. Commercial and Residential Hourly Rates for HVAC Crew

Crew Q-5	Commercial Hourly Rate	Residential Hourly Rate
1 Steamfitter	$98.10	$68.65
1 Steamfitter Apprentice	$78.50	$54.90
Total	$176.60	$123.55

Source: Authors' estimates