Title

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Original article

Benefits and challenges in deployment of low global warming potential R290 refrigerant for room air conditioning equipment in California

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ABSTRACT

High global warming potential gases (“high GWP”) are the fastest growing sector of greenhouse gas emissions in the world and in California and are primarily used as refrigerant gases in refrigeration and cooling equipment. Hydrofluorocarbons (HFCs) refrigerants are the dominant type of high GWP gases with GWP values thousands of times larger than CO_2 on a 100-year timescale. Refrigerant-grade propane (“R290”) has a very low GWP (GWP = 3.3) with good thermodynamic properties and good cooling equipment performance but the flammability of any leaked refrigerant makes equipment design, handling, and maintenance critical factors to manage. This paper focuses on the potential climate benefits and costs of transitioning to R290 refrigerant in small room air conditioning (AC) units, specifically window AC, packaged terminal AC/heat pumps (PTAC/PTHP), and mini-split heat pumps. Overall climate impact for a transition to all three types of air conditioning units in the 2022–2051 timeframe is found to be from 15 to 64 million metric tons of greenhouse gas (GHG) savings in California with a cost of saved CO_2eq that ranges from $14.50 per ton of CO_2eq saved to −$50.30 per ton of CO_2eq saved (net savings) depending on whether the baseline refrigerant is R32 or R410A and depending on the relative energy efficiency for R290 units compared to baseline units.

Introduction

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/heat pump equipment and in other uses such as spray foams and fire extinguishers. The current baseline refrigerant gases are hydrofluorocarbons (HFCs). Commonly used HFC refrigerants today are classified as “A1” or non-flammable with low toxicity as per ASHRAE standard 34–2019. Though these HFC refrigerants are non-ozone depleting substances (non-ODS), they are high global warming potential (high GWP) refrigerants with GWP values that are hundreds to thousands of time more potent than CO_2 on a 100-year time horizon using GWP values from the IPCC Fourth Assessment Report [1]; e.g. R410A has a GWP value of 2088).

Internationally, the Kigali Amendment to the Montreal Protocol was approved in 2016 as part of the United Nations Environmental Program “Meeting of the Parties”[2]. The goal is to achieve over 80% reduction in HFC consumption by 2047. As of October 3, 2023, 155 countries including the United states have ratified the amendment.

Many low or lower GWP refrigerant alternatives are “mildly flammable” (A2L classification) or “flammable” (A3 classification). Current HFC-based refrigerants are class A1 (non-flammable, lower toxicity) while most refrigerants with GWP < 750 for air conditioning are Class A2L (mildly flammable, lower toxicity) or Class A3 (flammable, lower toxicity). “Low GWP” typically refer to refrigerants with GWP less than 150. Class A2L and A3 refrigerants require specific safety standards for handling and equipment maintenance.

In California, High GWP gases resulted in 20MMt CO_2eq per year in 2018 and are considered as the fastest growing GHG sector[3]. This represents 4.7% of 425 MMt total emissions in 2018. In California, HFC emissions constitute 98% of GHGs from the High GWP gases sector.

California has aggressive climate targets in place with SB 1383 (40% reduction of HFCs in 2030 relative to 2013 baseline) and is more stringent for F-gas reduction than the recently concluded Kigali amendment to the Montreal Protocol. However, additional regulation is

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required for the state to meet the 40% reduction goal in 2030 [27]. In particular State Bill 1206 (SB-1206) requires the state air resources board (ARB) "to initiate a rulemaking requiring low and ultra-low global warming potential alternatives to hydrofluorocarbons", transitioning to ultra-low or no global warming potential alternatives no later than 2035. The bill defines "ultra-low GWP" as less than 10 [4].

This paper is the first to quantify the costs and benefits of R290 (A3) refrigerant (refrigerant grade propane) for room air conditioning in the largest state in the U.S., California. We discuss the rapidly evolving global, national (U.S.), and state policy environment, the net consumer costs and overall greenhouse gas savings for the next 30 years in California with a transition to R290 in room air conditioning from current high GWP hydrofluorocarbon (HFC) refrigerants. This is particularly relevant since the globe and the state is warming at an increasing pace, heat waves are become more frequent and severe, and the demand for room AC is expected to grow sharply over this time frame. R290 is a readily available, high quality refrigerant that is being more widely adopted in Asia and the European Union and studies such as this are important to highlight the GHG savings opportunity and low cost of carbon for R290-based room air conditioning equipment in the largest economies such as California.

Sources of GHG emissions from refrigerant gases include direct and indirect emissions. Direct sources include any leakage of refrigerant during manufacturing, distribution, installation, during equipment operation and operating lifetime, and any refrigerant loss during end-of-life disposal. Indirect emissions are those GHG emissions that are due to any GHG emissions from the electricity generation that powers the cooling equipment. Thus, estimating the overall climate impact from more energy efficient equipment designs and lower GWP refrigerants is an active area of investigation (e.g., [5]).

R290 as an alternative refrigerant

R290 or refrigerant-grade propane is a promising alternative refrigerant that is non-ozone destroying and has a GWP value of 3.3. Propane and other alternative refrigerants (R32, R466A, and R452B) are identified as promising in air conditioning[6].

Hydrofluoroolefins (HFOs) and their mixtures can be valid alternatives as efficient, low-GWP, less flammable A2L refrigerants than HCs and, usually, require a few modifications of the cooling system when replacing HFCs[7].

However, there are concerns with per-and polyfluoroalkyl substances (PFAS) accumulation when common HFCs and HFOs are released and the impact of PFAS on human health and the environment. This is highlighted in the 2024 EU F-Gas regulation[8]and there is a proposal to ban virtually all the current lower GWP HFC/HFO alternative refrigerant blends[9].

Each alternative refrigerant has strengths and weaknesses based on a wide range of criteria such as environmental impact (e.g., GWP value, toxicity), compressor impact (e.g. compressor capacity, glide), heat exchanger impact (e.g. heat transfer pressure drop), and system impact (e.g. compressor and system cost). For example, a recent simulation by [6] shows that for 3-ton unitary air conditioners, R290 has the best performance compared to R32, R466A, R452B, and R410A. Abdelaziz et al [10] conducted a comprehensive series of experiments to evaluate the energy performance of low-GWP alternative refrigerants in mini-split air conditioning systems. Compared to the R22 baseline, R290 drop-in tests showed 8% and 5% lower cooling capacity but 7% and 11% higher energy efficiency at AHRI test conditions A (95 °F (35 °C) outdoor ambient) and B (82 °F (27.7 °C) outdoor ambient), respectively. Research findings suggest that with dedicated redesign and optimization tailored to R290 refrigerant, it is possible to mitigate the loss in cooling capacity and further enhance energy efficiency. Nasution et al. [11] developed a room air conditioner using a liquid-suction heat exchanger. R290 was further used for system retrofit. Compared with the standard R22 air conditioner, the optimal system shows a significant energy efficiency improvement of 38.29% in COP.

As a low GWP refrigerant with good thermodynamic properties [12,13,14,31] 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 refrigeration circuits. Jeon et al. (2020) [36] investigated the seasonal performance and lifetime environmental factor of residential ejector-expansion air conditioners (EEACs) with low-GWP refrigerants. R290 emerged as the most promising working fluid for EEACs, with the highest cooling season performance factor and lowest total CO_2e emissions.

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-fueled outdoor grills. The usable amounts or propane are thus limited to reduce risk of ignition from any leaks and require careful handling and equipment design to minimize the risk of unwanted refrigerant loss, and to eliminate where possible any source of sparks within the equipment. Tang et al [15] studied the fire hazard of R290 in a household split-type air conditioning system. To reduce the leaking rate and risk, the authors proposed the installation of a solenoid valve behind the capillary. The results demonstrated that when the solenoid valve was closed, both the range and duration of the combustible zone were significantly reduced.

Propane is most readily adopted in smaller AC and commercial refrigeration equipment (CRE) systems where the unit is self-contained, charge limits are small (e.g. less than a few hundred grams) and factory-installed, risks from ignition contained, and safety precautions managed within the factory. Zhou and Gan [16] employed micro bare-tube heat exchangers as the condenser and evaporator components in a split air conditioning unit, aiming to minimize the amount of R290 refrigerant needed in air conditioners and heat pumps.

In the U.S., EPA 2015 charge limits for room AC products as a function of cooling capacity is shown in Fig. 1 below along with the UL 484 charge limit. Acceptable charge sizes increase more or less proportionally with the height at which the equipment is typically installed (those 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 g for A3 refrigerants in room ACs [17]effectively precludes the use of propane in all but the smallest window AC (e.g., [32]) and PTAC/PTHP units.

The US EPA does not allow split AC systems with R290. However, the new IEC international standard (IEC 60335–2-40 Edition 7.0 [29]) for higher charge limits for HCs such as R290 was approved in April 2022 allow up to 988 g of R290 in a standard split air conditioning system in new equipment designed according to certain additional safety requirements to ensure safety is not compromised (e.g. enhanced tightness and properly designed airflow). As noted above, the state of California has increasingly stringent climate targets for new refrigeration and air conditioning equipment and mandates a transition to ultra-low or no global warming potential alternatives no later than 2035.

This paper presents the costs and GHG benefits of a transition to room AC (window AC, mini-split AC and packaged terminal AC and heat pumps) with propane refrigerant in California for the first time. The paper describes the analysis approach in Section 2 followed by results in Section 3 and then a conclusion section summarizes the outlook for R290 in room AC in California.

Methods/ approach – Modeling and Cost-Benefit analysis

The technical approach is described below for equipment costing, lifecycle costs, and California net impact analysis over the next three decades for GHGs and customer costs.

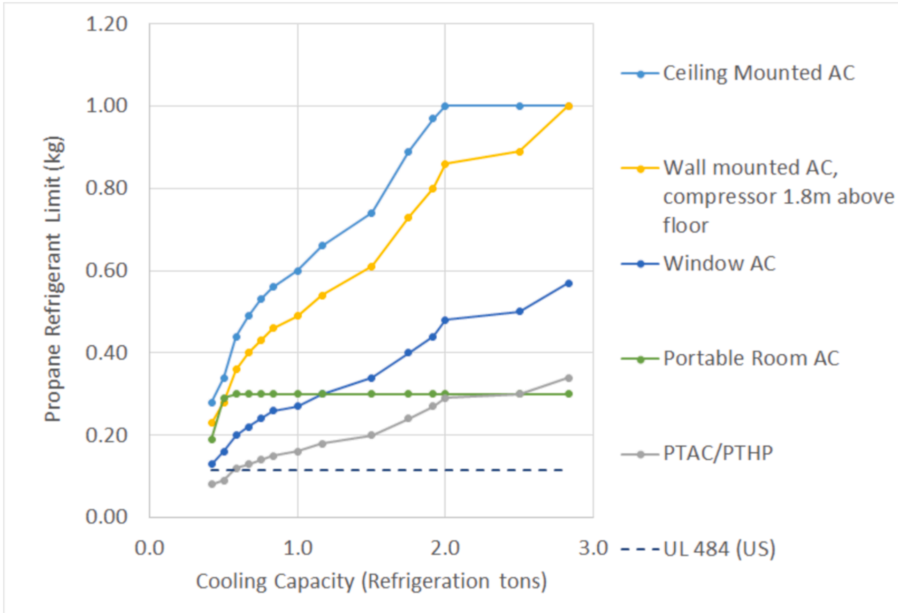

Fig. 1. Allowable R290 charge sizes for US EPA, and US UL. Sources: EPA 2015 [28] ("Ceiling, Wall, Window, Portable, PTAC/PTHP"); [17] ("UL 484").

Equipment cost methodology

The additional manufacture and installation costs of air conditioning equipment utilizing R290 as a refrigerant compared to R410A were established by analyzing the following: (1) the manufacturer cost impacts of including safety components in an air conditioner that utilizes R290; (2) the manufacturing and process changes required to ensure that R290 air conditioners are produced safely; (3) additional costs for the compressor suitable for R290; and (4) manufacturing factory changes required for the installation of air conditioners utilizing R290. (R290 costs compared to R32 are in SI).

The safety standards in IEC 60079[18] were used as a guide to identify the electrical components required for an air conditioner charged with an A3 refrigerant, such as R290. The safety standard requires that: (1) plastic fans rather than metal be utilized to ensure spark-resistance; (2) direct current (DC) motors and solid-state components be utilized to ensure both spark-resistance and the prevention of points of hot surface ignition; and (3) the inclusion of additional components for refrigerant leak detection and controls to power down the air conditioner in the event of a refrigerant leak.

In order to establish the cost of the electrical components of an R290 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 need to be replaced to prevent potential sources of ignition if a refrigerant leak occurs; (2) additional cost for an R290 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 the "existing parts analysis," a bill of materials (BOM) for both a mini-split air conditioner and a window air conditioner were acquired in order 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 in order 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.

For the "existing parts analysis," the BOMs for a Fujitsu mini-split air conditioner (model ASU9RLF1 and AOU9RLFW1) [19] and a Midea window air conditioner (model MWEUK18CRN1MCK8) [20] were obtained. Literature sources were used for R290 compressor incremental cost. More details are provided in the SI.

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 a good estimate of the relative cost increase of components required to ensure compliance with the IEC safety standards. 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. Table 1 shows the additional parts required for the primary and redundant systems in the Fujitsu mini-split air conditioner and the Midea window air conditioner.

Our starting assumption is that R290 units have performance that is matching current R410A units but with some cost increase since manufacturers have no requirement to exceed current performance standards. A recent simulation [6] shows that for 3-ton unitary air conditioners, R290 has the best performance compared to R32, R-466A, R-452B, and R410A. Thus, as a sensitivity we look at the case where R290 units have some cost increase but also improved performance.

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

Table 1
Primary and Redundant Safety System Components for R290 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.

expense over the life of the system, including purchase, installation costs and operating costs. The sum of the equipment purchase and installation cost is called 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 summed to provide the total lifetime operating expense (LOX). The LCC is equal to the sum of these two components:

$$LCC = TIC + LOX$$

Fig. 2 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. Detailed description of the inputs to the LCC analysis and assumptions for operating hour distributions are provided in the SI.

For each equipment type, the LCC is calculated for a sample of 10,000 consumers. For PTAC/PTHP 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 (discussed further below) are drawn from distributions. LCC results are presented for several scenarios below.

Approach for California impact analysis

The purpose of the California impact analysis is to calculate the cumulative impacts to customer costs and GHG savings over a 30-year time period.

Shipments model: 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 period (2022–2051). The reference shipments model is composed of installation into new construction and replacements of existing units. More details for the shipments model assumptions are in the SI.

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 R410A or R32 to R290. We modeled two key sets of scenarios: the first assumes a switch from R410A/R32 to R290, with no corresponding change in energy efficiency, the second set assumes a switch from R410A/R32 to R290 and a corresponding 10% increase in energy efficiency. Additional GHG modeling assumptions are in the SI.

Results

Equipment Cost Analysis Results

Equipment cost analysis for R410A shifting to R290 for a mini-split AC is presented here. (Midea window AC cost analysis for R410A shifting to R290 and equipment cost analysis for R32 shifting to R290 is provided in the SI.) Table 2 shows the full analysis results for the Fujitsu mini-split air conditioner (details for the mini-split and window AC cost analysis are in the SI).

Cost summary

The cost analysis conducted above indicates that R290 mini-split, package terminal, and window air conditioners would incur a manufacturing production cost (MPC) increase relative to R410A based designs of approximately 3%, 5%, and 7% respectively for the incorporation of primary and redundant safety systems. For the life cycle cost analysis and net-impact analysis below, MPC cost increases of 3%, 5%, and 7% are assumed to be representative for incorporating R290 in current mini-split air conditioner, packaged terminal air conditioner (PTAC), and window AC designs with R410A 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

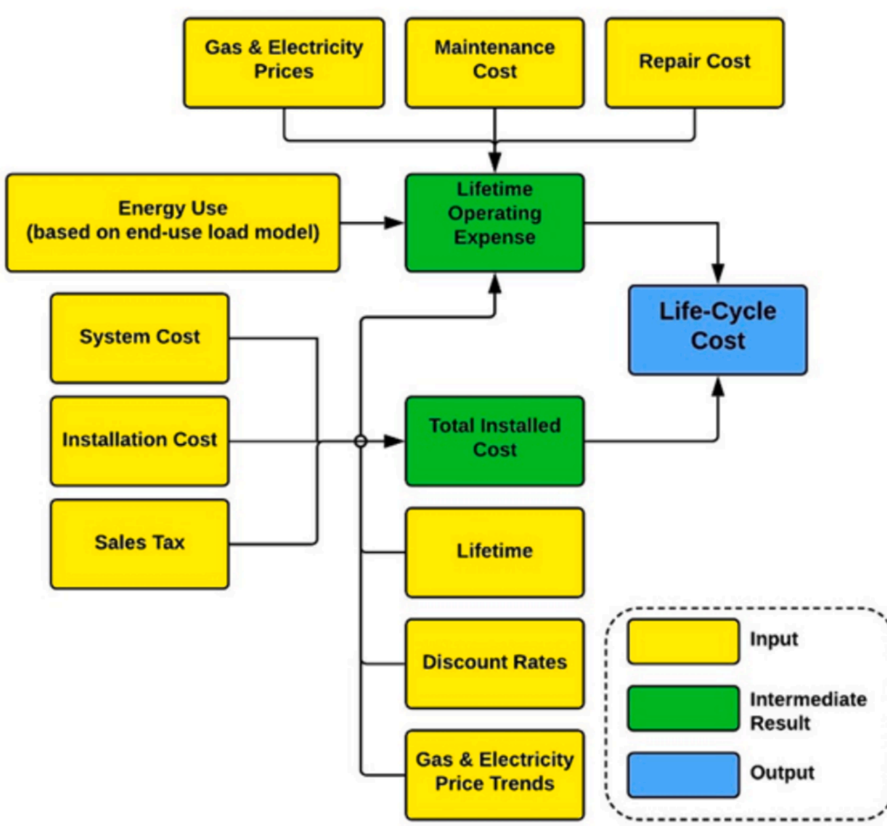

Fig. 2. Schematic of the Life-cycle Cost Calculation.

Table 2
R290 Fujitsu Mini-Split Air Conditioner Manufacturer Product Cost Increase from R410A.

SEER	2-ton Central Air Conditioner MPCs*						R-290 Safety: Purch. Parts Increase	Adjusted MPCs for R-290 Fujitsu Mini-Split						
	Materials		Labor	Over-head	Deprecia-tion	Total MPC		R-290 Purch. Parts Incr.	Compress-or cost increment	Factory upgrade cost [37]	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
	Total	Purch. Parts Frac.**												
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%

* Sources: U.S. DOE TSD, Residential Central Air Conditioners and Heat Pumps, Direct Final Rule. Chapter 12, Section 12.3.5. December 2016 [34]; Authors' calculations.
** Purchased Parts Fraction is 53% 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 [33].

and capacity of PTAC are intermediate between these two AC types. As described in the SI, we estimate that incremental costs for shifting from R32 to R290 based designs are 1.5%, 2.5%, and 3.5% or about one-half of the incremental cost of R410A for mini-split, package terminal, and window air conditioners, respectively.

These cost estimates may represent the higher end of incremental equipment cost for small air conditioner units with R290 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.

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 above [21].

Life cycle cost (LCC) results

Results from the LCC analyses for the scenarios considered here are summarized in Table 3. and S2 (SI). From the above equipment cost analysis, for R410A to R290, the manufacturer price increases are 7%, 5% and 3% for window AC, PTAC/HP and Mini-split HP 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, which have been taken from the 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. Window AC has the smallest 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 specific consumer rebates.

California impact analysis results

GHG scenarios and potential savings for 2030, 2050

The primary GHG benefit in this analysis is the switch from R410A or R32 to R290 refrigerants. Global warming potential (GWP) is used to measure the climate benefits of R290 relative to R410A. GWP measures the climate damage of various substances relative to CO_2 (which has a GWP of 1). The GWP of R410A is 2,088, the GWP of R32 is 675, and the GWP of R290 is 3.3 [22].

Therefore, with its comparable efficiency to baseline HFCs, a transition to R290 will have a significant climate benefit through the reduction of direct GHG emissions from refrigerant release to the environment. California's grid-supplied electricity is rapidly decarbonizing with a net zero GHG goal in retail sales by 2045 [25] so the fraction of indirect emissions is becoming smaller over time.

Table S3 in the SI 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 climate benefit from R290 is measured by comparing the amount of leaked refrigerant in a year with the difference in GWP between R290 and either R410A or R32. The total amount of avoided CO2e 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 S4 and Figure S5 (SI) displays the avoided CO_2eq in tons for the transition to R290 from the two baseline refrigerants.

Table 4 below shows the annual and cumulative avoided refrigerant emissions in tons of CO_2e for R410A to R290 and R32 to R290. Window AC represent 40% and 42% of the cumulative savings, respectively.

Starting in 2023, all newly installed small AC in California will need to have refrigerants with GWP less than 750 (Central Systems have to comply beginning in 2025). We assume here that PTACs, PTHPs, and Window ACs would qualify as Small AC and will transition to R32 (GWP = 675) in 2023 and Mini-splits will transition to R32 in 2025. In this case of R32 as the new "lower GWP" baseline, a transition to R290 will have a

Table 3
Total Installed Costs for the Baseline, R410A to R290, and R32 to R290 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	–
R410A to R290	$3,900	$75	$1,486	$43	$1,626	$46	$466	$26
R32 to R290	$3,862	$37	$1,465	$21	$1,603	$23	$453	$13

Source: Authors' calculations.

Table 4
Annual and cumulative avoided refrigerant emissions.

Year	R410A to R290		R32 to R290	
	Annual Avoided Emissions (tons CO_2eq)	Cumulative Avoided Emissions (tons CO_2eq)	Annual Avoided Emissions (tons CO_2eq)	Cumulative Avoided Emissions (tons CO_2eq)
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.

smaller savings in avoided direct emissions. For the case of transitioning from a baseline of R32 to R290, the cumulative avoided emissions in 2050 is reduced to 8,635,456 tons of CO_2e from 37,182,436 when using R410A as the baseline.

Table 5 below shows the NPV for the next 30 years for shifting to R290 refrigerant from either a R410A baseline or a R32 baseline. For the R32 baseline, there is an additional cost of $217 million to switch to R290 and for R410A baseline there is an additional cost of $452 million to switch to R290. For R32, the avoided direct emissions for the full equipment lifetimes to 2080 are 15.1 MMt CO_2eq while for R410A, the savings are 61.9 MmtCO_2e. (Note that 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 still in the field after 2050). This corresponds to a cost per ton-CO_2eq saved of $14.37 and $7.31 respectively. Window AC costs are $16.83/ton-$CO_2$eq and $8.75/ton-$CO_2$eq for R32 and R410A, respectively.

High-Efficiency air conditioner adoption scenario

Here we assume that the low-GWP refrigerants are used in equipment that is 10 percent more efficient than the current federal baseline (Table S4; and [6,26]) and that equipment costs for R290 are 10% higher than the baseline refrigerant R410A. This results in not only environmental benefits from avoided refrigerant emissions, but reduced purchased electricity from utilities and consumer utility bill savings.

The unit energy consumption (UEC) in Table S4 refers to the on-site energy consumption. In order to calculate the total energy saved, it is important to account for the site energy use as well as energy losses associated with generation, transmission, and distribution of electricity, as well as the energy consumed in extraction, processing, and transporting energy, referred to as the full-fuel-cycle electricity use. For this, we use a full-fuel-cycle multiplier from the AEO 2021 [35] that is applied to the site electricity savings in each year of the analysis period.

Table 5
Cost per ton of CO_2eq saved for R290 vs R32 and R410A.

Baseline refrigerant	NPV, 7% discount rate (millions$)	Avoided refrigerant (million tons CO_2e)*	Cost per Mt-CO_2eq saved ($)
R32	−217	15.1	14.37
R410A	−452	61.9	7.31

*Avoided refrigerant emissions timeframes extends through 2080 to account for equipment lifetime of installed equipment. *Source: Authors' calculations.*

Other assumptions for this scenario are detailed in the SI.

Table S6 and S7 shows the results for shifting to R290 from R410A and R32, respectively.

In this case (Table 6), the operational cost savings of R290 leads to $850.3 million in net savings compared to R32 and $562.4 million in net savings over the 30-year time frame compared to R410A. Here, there is a net savings and a negative cost for CO_2 saved, or a savings of $50.30 and $8.80 per ton of CO_2eq saved for R32 and R410A, respectively. Window AC are −$28.52 and −$3.72/ton-CO_2eq saved for R32 and R410A, respectively.

The most favorable products for A3 refrigerants are small capacity window air conditioners which 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 and that are not self-contained such mini-split air conditioners.

We comment on each of the three room-air conditioning product types below.

- **Packaged Terminal Air Conditioners** are considered to have a higher relative flammability risk since these units are typically installed very low to the ground. Thus, any leaking refrigerant has greater chance to pool on the ground and has less distance and room to dissipate in traveling from leakage location to the ground.
- **Window Air Conditioners** viewed as 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 refrigerant leak. Window ACs have a larger annual unit sales volume than either PTACs or mini-split ACs.
- **Mini-split Air Conditioners** are typically ductless air conditioners with high energy efficiency that have refrigerant lines to an outdoor condensing unit. As such, they are typically charged onsite by technicians and thus 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 in the U. S. due to this concern.

Discussion

Some gaps for the deployment of room ACs with R290 include the

Table 6
Total GHG savings for the case where R290 AC units have 10% higher energy efficiency than baseline refrigerant over next 30 years.

Baseline refrigerant	NPV, 7% discount rate (millions $)	Electricity grid GHG emissions saved (million tons of CO_2e)	Avoided refrigerant (million tons CO_2e)	Total GHG saved (MMt-CO_2e)	Cost per ton-CO_2eq saved ($)
R32	850.3	1.8	15.1	16.9	−50.30
R410A	562.4	2.82	61.9	64.0	−8.80

[1]The electricity grid GHG emissions saved vary due to the different shipments analysis periods (2022–2051 for R410A, 2023/25–2052/54 for R32).
Source: Authors' calculations.

lack of harmonized policy signals, much less market incentives, for manufacturers to pursue R290 in small window air conditioners. Harmonized policy between UL safety standards and EPA charge limits would provide a clearer signal to manufacturers for small room ACs on acceptable designs and could be followed by incentives, rebates, or other "market-pull" mechanisms to encourage market development.

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 (e.g. PTACs designed for mounting higher above the ground or above windows and or novel integration approaches with thermal storage [e.g. [23]) can be done to further improve unit-level performance and reduce the risks of refrigerant leakage.

Dedicated redesign and optimization should be tailored to R290 refrigerant to mitigate any capacity loss and improve energy efficiency. Small capacity R290 ACs are commercially available and have been utilized in some markets, such as EU markets, provided that the charge size meets regulatory requirements. In other work, we have conducted component-level design simulations, testing, and prototyping to further enhance the system cost and energy performance of commercialized R290 air conditioning units (Ding et al. 2024 [26]), which is out of scope for this paper.

Another key limitation of this work is that it does not cover flammability risk or charge limits for R290. The costing analysis here contains redundant safety system and the analysis covers small AC unit capacities and small charge sizes of less than 200 g, all of which contains the flammability and safety risks. As mentioned above, the EU F-Gas regulation has increased charge limits considerably above this with regulatory requirements. Extensive work has been done by the refrigerant manufacturers and equipment manufacturers in the past on alternative refrigerant testing and evaluation. The Air Conditioning, Heating, and Refrigeration Institute (AHRI) Safe Refrigerant Transition program has also performed extensive research on flammable refrigerants [24] including investigations on the proper basis for setting charge limits for A2L and A3 refrigerants. Many past studies also consider the risks of R290 in residential split AC and risk mitigation approaches (e.g. [15] and [30]).

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

Conclusions

Flammable refrigerants (class "A3") hydrocarbon gases such as propane have significantly lower GWP value than conventional HFC refrigerants. They are widely available, and have good thermodynamic properties for air conditioning equipment. The key concern for A3 refrigerants is their flammability risk which must be carefully managed in the equipment design and manufacturing and equipment maintenance and repair in particular, but could also pose some risk to the consumer if there is a refrigerant leak during the equipment's operating life.

Small, self-contained air conditioning units are the most accessible market segment for flammable refrigerants because the equipment's refrigerant is installed (charged) at the factory, the equipment is an enclosed box without exposed refrigerant lines, and refrigerant quantities (or "charge sizes") are relatively small, e.g., less than 150–200 g. Room air conditioning units that are installed higher above the floor can support more refrigerant charge and are less of a safety risk since there is higher potential for refrigerant dispersion compared to equipment that is installed closer to the ground. This paper has the following key conclusions:

1. Cost analysis here indicates that R290 mini-split, package terminal air conditioners, and window air conditioners would incur a manufacturer production cost increase relative to R410A based designs of approximately 3%, 5%, and 7%, respectively for the incorporation of primary and redundant safety systems of $75 to $26.
2. Small window AC with R290 represent the most favorable point of market entry for room ACs with R290 since they are self-contained units, can meet the EPA 2015 charge limit and as with other product types, and have room for further performance improvement. PTACs with R290 are less favorable for market entry since the units tested were not meeting the EPA charge limit and PTACs are also typically installed lower to the ground than window ACs. Mini split heat pumps with R290 are not currently allowed by the EPA since they typically have refrigerant installed onsite, are not self-contained, and have the highest relative risk for R290 leakage.
3. The current UL 484 (UL 60335-2-40) limit of 114 g or less of R290 per AC unit [17] is a much tighter limit than the EPA 2015 limits for all but the smallest units and does not consider varying room sizes and varying installation heights. This precludes room ACs with R290 from being developed for the room AC market segment in California. In contrast, international safety standards have approved a proposal for higher refrigerant change limits in April 2022 with maximum R290 charge up to 0.998 kg.
4. We estimate a cumulative potential savings of 8.6–37.2 MMt CO2eq over the next 30 years in transitioning to small room AC with R290 refrigerant, at a net cost of about $7 to $14 per ton of saved CO2eq with 1.5% to 7% higher equipment cost and equivalent efficiency to baseline HFC refrigerants R32 and R410A. For window air conditioners with R290 and the same energy efficiency as baseline R410A refrigerant and a 7% increase in cost, the life-cycle cost increase is $26 or about 3% higher total lifecycle cost. Hence, a subsidy or rebate program that refunded the buyer $26 of the unit purchase price would be enough to ensure that about all consumers have a neutral economic impact under this scenario.
5. For the sensitivity case of 10% higher efficiency with R290, there is a net savings of switching to R290 from R410A and R32 of $8.80 and $50.30 per ton of saved CO_2eq, respectively (or equivalently, negative cost) over the next 30 years since the savings from lower electricity costs outweighs the slightly higher equipment costs.

CRediT authorship contribution statement

Max Wei: Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Chao Ding:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Greg Rosenquist:** Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **Katie Coughlin:** Writing – original draft, Methodology, Formal analysis, Data curation. **Ed Cubero:** Writing – original draft, Methodology, Formal analysis, Data curation. **Tom Burke:** . **Omar Abdelaziz:** Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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