Refrigerants, taking the chill out of heat pumps

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ABSTRACT

While the mass adoption of heat pumps will be instrumental in achieving carbon reduction goals, it is important to consider the greenhouse gas (GHG) impacts from the refrigerants in heat pumps and the air conditioners they frequently replace. Refrigerants in air conditioners and heat pumps in operation today commonly have heat-trapping properties 2,000 times more potent than carbon dioxide (CO2). Alarmingly, GHG emission data from the U.S. Environmental Protect Agency (EPA) and the California Air Resources Board (CARB) indicates that refrigerants in small commercial and residential air conditioners and heat pumps get emitted or vented into the atmosphere between 40 and 99% of the time after these systems are retired.

This paper presents a two-pronged approach for managing refrigerants to greatly reduce their climate impacts, based on 1) the adoption of low-global warming potential (GWP) alternative refrigerants and 2) innovative strategies for maximizing end-of-life refrigerant recovery and minimizing refrigerant leakage. The paper also reports on the GHG impacts that refrigerants could and should have in conjunction with heat pump adoption, explores current and future opportunities for adopting emerging low-GWP refrigerant alternatives and natural refrigerants in heat pumps, and shares the expected timelines of availability in North America. In addition, it shows how the above actions translate into financial savings using the California Public Utility Commission's Refrigerant Avoided Cost Calculator.

The basis for these findings is secondary research, in-depth interviews with over twenty HVAC contractors, refrigerant reclaimers, and policymakers, a focus group, a contractor web survey, and original analysis.

Introduction

The electrification of HVAC and domestic hot water systems is at the core of nearly every net-zero-emission pathway. Today heat pumps serve as the de facto high-efficiency electrification option for residential and light commercial HVAC and domestic hot water (DHW) systems. Heat pumps are commonly portrayed as a zero-emission appliance when powered by a renewable power grid but this only accounts for energy-related emissions. Heat pumps and the air conditioning systems they often replace all contain some type of working fluid or refrigerant that transfers heat from one space to another, which poses an ongoing risk for greenhouse gas (GHG) emissions. The standard refrigerant installed in most new HVAC systems today is the hydrofluorocarbon (HFC) blend R-410A. The 100-year global warming potential (GWP) of R-410A is 2,088 (Forster, et al. 2007). This means over a 100-year period, R-410A will trap 2,088 times more heat than the same mass of CO_2. Table 1 presents the various GWP rating categories and some of the common refrigerant types found within each category.

Table 1. GWP ratings and common refrigerants

GWP rating	100-year GWP	Common refrigerants (100-year GWP)
High GWP	>750	R-410A (2,088), R-22 (1,810), R-134a (1,430), R-404A (3,922)
Lower-GWP	151-749	R-32 (675), R-454B (466), R-513A (630),
Low-GWP	10-150	R-516A (140), R-457A (137), R-454C (146)
Ultra-Low-GWP	<10	R-1234ze/yf (1), R-1233zd (1)
Natural refrigerants	<4	R-744/carbon dioxide (1), R-290/propane (3), R-600a/isobutane (2), R-717/ammonia (0)

The high GWP of refrigerants is a significant concern because all systems containing refrigerant are prone to leakage both during the system's lifetime and after it is retired. These concerns are well known, and there is currently an array of global, regional, and domestic laws and agreements in place to help mitigate the GHG impacts of refrigerants. However, the process is slow and the timeline for eliminating high-GWP refrigerants in HVAC, heat pump appliances, and refrigeration systems is still decades away. While new lower-GWP refrigerants are emerging in the market, the industry currently lacks adequate training to correctly install these lower-GWP refrigerants and employ best practices to minimize operational leakage, properly size systems, and identify opportunities to install weatherization measures. The existing HVAC stock will continue to leak refrigerant for decades to come, with end-of-life leakage having the worst impacts on warming.

The U.S. Department of Energy's publication, "Decarbonizing the U.S. Economy by 2050," calls for building heating, cooling, and refrigeration equipment with 100-year GWP levels <10 to be widely available by 2035 (Langevin, et al. 2024). Fortunately, natural refrigerants like CO_2 in grocery store refrigeration systems, and R-600a (Isobutane) in refrigerators, are quickly becoming standard practice for new systems. Flammability concerns and charge size limits will likely prevent the widespread U.S. adoption of natural refrigerants in HVAC heat pumps for another five to ten years. Several mildly flammable lower-GWP refrigerant options have emerged as interim refrigerant options for new light-commercial and residential HVAC equipment. The major original equipment manufacturers have publicly announced plans to either use R-32 (675 GWP) or R-454B (466 GWP). While both represent a significant GWP improvement over R-410A, both come with tradeoffs.

It is crucial that the billions of dollars in incentives and tax breaks targeting new heat pump installations always consider the overall GHG benefits are maximized. This paper combines the findings from in-depth interviews, secondary research, an HVAC contractor web survey, a focus group on the current low-GWP refrigerant transition, and analysis on the GHG impacts stemming from heat pump adoptions to show the overall environmental impact the heat pump revolution could and should have. Key findings and recommendations present a two-pronged approach for managing refrigerants to greatly reduce their climate impacts, based on 1) the adoption of low-global warming potential (GWP) alternative refrigerants and 2) innovative strategies for maximizing end-of-life refrigerant recovery and minimizing refrigerant leakage.

The Heat Pump Revolution

The International Energy Agency's NZE roadmap for limiting global warming to 1.5 °C calls for 20% annual heat pump growth rates between 2022 and 2030 globally (IEA 2023). The Inflation Reduction Act of 2022 is offering a combination of customer rebates, tax incentives, and workforce development funding targeting new HVAC and DHW heat pumps. Like any green technology, heat pumps have elicited some criticism over the years. Homeowners voice genuine concerns about added installation costs, electric panel-sizing challenges, and cold-climate performance issues to name a few. A 2024 study sponsored by the U.S. Department of Energy, "Heat Pumps for All?," looked at many of these issues to examine the potential benefits of heat pumps. The study provides a salient breakdown of the potential GHG reductions and lifecycle cost benefits that three air-source heat pump (ASHP) performance tiers would achieve across a vast array of U.S. housing types and climate zones (Wilson et al. 2024). Several key findings from the study to note include:

- "ASHPs deliver substantial energy savings and reduce average GHG emissions in all states and future grid scenarios. (p.4)"
- "All six scenarios also included sealing and insulating all ducts located in unconditioned space down to 10% leakage and R-8 (RSI-1.4) insulation. (p.21)"
- "Cost reductions are needed to improve the value proposition for almost half of all US households. (p.9)"

The Inaugural Heat Pump Summit held in November of 2023, included an array of plumbers, HVAC contractors, heat pump vendors, original equipment manufacturers (OEMs), policymakers, program implementers, and heat pump experts.[1] The summits stressed that the transition away from natural gas and other fossil fuel heating systems to heat pumps is imminent in California but is ripe with technical challenges. Key technical challenges include:

- Customers prioritizing cheap same-day solutions over long-term quality
- Electrical panel configuration
- Sizing the system according to loads (instead of oversizing to avoid call backs)
- Proper duct configuration and adequate airflow

The challenges highlight the need for a knowledgeable workforce that implements best practices over rushed same-day retrofits. While the Heat Pump Summit, the DOE ASHP study, and the countless press releases touting the benefits of heat pumps all provide a valuable message, they offer little discussion around refrigerants.

Refrigerant Emissions

All HVAC, refrigeration, and heat pump systems with refrigerants are prone to leak during operation, maintenance, and at the end-of-life. Refrigerant emissions data collected by the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board (CARB)

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[1] The inaugural U.S. Heat Pump Summit was held in Berkeley, California at UC Berkeley on November 13, 2023. https://www.heatpumpsummit.org/hps-2023 .

shows that equipment with larger charge volumes like grocery store refrigeration systems and HVAC chillers, have high operational leakage rates (10-33% of full system charge **annually**). CARB and EPA data sets show that end-of-life leakage rates are highest for smaller commercial and residential systems. CARB estimates that the refrigerant remaining in central residential heat pumps and AC systems leaks or is intentionally vented into the atmosphere 80% of the time (CARB 2022). When released into the atmosphere, 80% of the remaining R-410A refrigerant in a 2.5-ton capacity central residential heat pump has over 60% of the global warming impact than the lifecycle emissions avoided by replacing the furnace and air-conditioning system with the heat pump in the first place.[2] Table 2 presents CARB-reported operational (average annual leak rate), end-of-life loss rate, and other emissions estimates by device type.

Table 2. 2022 CARB California emission inventory data

Device type	Average refrigerant charge size in lbs. per unit	Average annual leak rate of full system charge	Average end-of-life loss rate of remaining refrigerant	Percentage of refrigerant charge lost during lifetime
Residential heat pumps	8.2	5.3%	80%	147%
Residential unitary AC	7.5	5%	80%	143%
Window/room/wall AC and packaged terminal AC (PTAC) units, residential	1.54	2%	99%	99%
Commercial unitary AC, < 50-lbs., < 135,000 BTUh size (includes heat pumps)	18.2	5%	56%	127%
Commercial unitary AC 50-200 lbs., > 135,000 BTUh size	70	7%	20%	160%

It should be noted the refrigerant leakage rates reported by CARB differ from those reported by the EPA. End-of-life refrigerant loss rates reported by CARB are significantly higher than those reported by the EPA (80% for CARB vs 20-40% for EPA) while the EPA reports higher operational leakage rates than CARB (5.3-11% for EPA vs 5.3% for CARB) when looking at residential unitary AC systems (EPA US GHG). The authors of this paper recognize the complexity of accurately estimating refrigerant emission rates but consider CARB emission rates to be more accurate for two reasons:

1. A whitepaper published by the Yale Carbon Containment Lab looked at EPA's annual reclamation volume reports in combination with data reported by reclaimers and estimates, "that refrigerant recovery rates in the U.S. hover between 8 and 20 percent." (Yale 2023)

[2] Assumes 2.5-ton residential heat pump contains a full R-410a refrigerant charge of 8.2 lb. end-of-life emission is calculated using the California Public Utility Commission's Refrigerant Avoided Cost Calculator showing 5.6 lb. charge is emitted, resulting more than 5 tCO_2e emissions. Compared to the lifecycle emissions savings, 8.1 tCO_2e, of the SWCH045 DEER measure, Offering Q, packaged heat pump (SEER ≥ 18, HSPF ≥ 9.5) replacing packaged AC (SEER 15) and gas furnace (TE 80%), CZ04, single family home.

2. Section 608 of the Clean Air Act prohibiting intentional venting of ozone-depleting substances and their replacements is in direct contrast to the end-of-life loss rates CARB reports. One way the EPA accounts for this disparity is to report higher operational leakage (up to 11% for residential heat pumps) however, prior research efforts suggest annual residential equipment leakage rates rarely exceed 5%.

Barriers Preventing Recovery

Both the EPA and CARB are actively taking steps to both improve end-of-life recovery/reclamation rates, but the changes will inevitably trickle down slowly. In October 2023, the EPA announced the Final Technology Transition Rules which requires owners of equipment containing 15 lb. of regulated refrigerants (with a GWP greater than 53) to track leakage rates and repair activities (EPA Technology 2023). This 15 lb. threshold reduces the previous 50 lb. threshold which means smaller commercial HVAC equipment will be monitored more closely but residential systems will not as they typically contain refrigerant charges below 15 lb.

Lack of enforcement is potentially the biggest barrier preventing improved recovery rates. A 2022 review of the EPA's enforcement history database found only 26 records when using the search term "venting" or "refrigerant." Further review found that only four of those records involved defendants being charged with intentional venting of hazardous refrigerant into the atmosphere and only one occurred in the last ten years (EPA Enforcement 2022). Additionally, the HVAC contractors interviewed reported they currently receive little to no compensation when returning recovered refrigerant to their distributors or directly to reclaimers. A 2024 California HVAC contractor web survey showed only half of respondents reported ever receiving payment for recovered refrigerant. Of the respondents who reported receiving payment, the average payment received was only $3/pound, as shown in Figure 1. At that price, a contractor would receive about $21 for returning the remaining 7 lbs. of refrigerant recovered from a typical residential split-system AC.

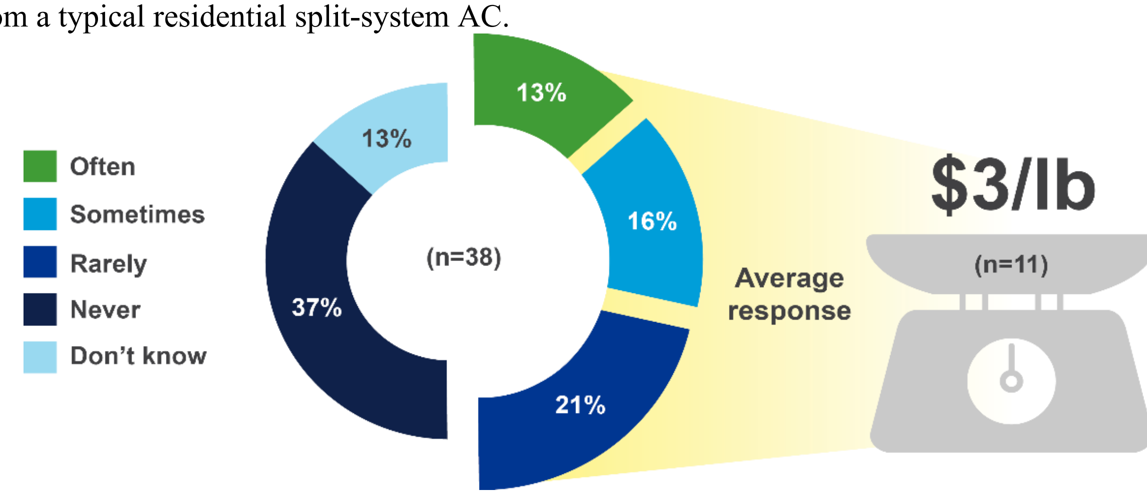

Figure 1. Frequency performed and compensation received for recovered refrigerant

The Transition to Mildly Flammable Refrigerants

The Kigali Amendment to the Montreal Protocol and the 2021 American Innovation and Manufacturing (AIM) Act will both serve pivotal roles in mitigating the global warming impact HFC refrigerants have. Both the Kigali Amendment and the AIM Act call for a gradual phasedown in HFC use. For the United States and other non-Article 5 countries, as defined by the Montreal Protocol, the phase down calls for an 85% reduction in HFC use by 2036. The U.S. Environmental Protection Agency (EPA) has begun enacting regulations to ensure the various industries that use HFCs will adhere to the 85% HFC reduction. In December of 2023, the EPA issued a final ruling on the use of HFCs in the Residential and Light Commercial Air Conditioning and Heat Pump Sector that calls for a 700-GWP ceiling to be applied to new residential and light-commercial HVAC systems beginning in 2025 (EPA 2023).

The Kigali Amendment and AIM Act will all make huge strides toward limiting new high-GWP refrigerants, but it will likely take decades before emissions really come down if more is not done. Most new HVAC equipment installed before 2025, and equipment manufactured prior to 2025,[3] will continue to emit high-GWP refrigerants for the lifetime of the equipment. In contrast, the timeline for the transition abroad varies by country. Many countries, particularly in Europe, have already implemented stricter regulations and are ahead of the U.S. in transitioning to low-GWP refrigerants. For example, the European Union's F-Gas Regulation aims to reduce HFC use by 79% by 2030.

Mildly Flammable Refrigerants (A2L)

In the United States, the current near-term solution to high-GWP HFC refrigerants like R-410A and R-134a is the transition to a series of HFC refrigerants that have a refrigerant safety classification of non-toxic, mildly flammable or A2L, such as R-32 and R-454B. R-32 and R-454B are both lower-GWP refrigerants that have emerged as interim options for new light-commercial and residential HVAC equipment. They represent a significant improvement over R-410A in terms of GWP, but both come with tradeoffs as shown in Table 2.

Table 3. R-32 and R-454B comparison across residential and small commercial HVAC applications

Refrigerant	Pros	Cons
HFC-32 aka R-32[4]	• Single-component refrigerant • No PFAS • Improved heating/cooling capacity* • Similar EER and COP efficiency* • Lower charge requirements*	• Mildly flammable • 100-year GWP 675
R-454B	• 100-year GWP 466 • Slightly improved cooling efficiency* • Slightly improved heating efficiency* • Lower charge requirements*	• Contains PFAS • Blended refrigerant • Slightly lower cooling capacity* • Lower heating capacity* • Mildly flammable

*Performance metrics compare an R-410 system with drop-in refrigerant testing of R-32 and R-454B at 95°F cooling and 47°F heating conditions.

[3] EPA final ruling on HFC phasedown, subsection (i), AIM act; allows sale, distribution, and export of certain high-GWP HVAC products after manufacture and import compliance date up to three years after compliance date.

[4] Because R-32 is comprised of a single refrigerant and not a blend of different refrigerants it is technically HFC-32 but is more commonly referred to as R-32.

The modeled performance of these two refrigerants is similar to R-410A, where each refrigerant may excel in some aspects but not others. For example, in a 2023 study R-32 outperforms R-410A in cooling capacity by 8% and heating capacity by 7%, while R-454B slightly outperforms R-32 in cooling efficiency by 3% and heating efficiency by 2% (Zhenning 2023). Both R-32 and R-454B show a decrease in the required system refrigerant charge by 16% for R-32 and 9% for R-454B, relative to an R-410A (Zhenning 2023).

Per and polyfluoroalkyl (PFAS) chemicals are a category of contaminates found in various industrial and consumer products since the 1950s. PFAS chemicals are sometimes called "forever chemicals" as they are very persistent in the environment and break down very slowly over time. PFAS chemicals have been detected in water, air, fish, and soil across the world (EPA PFAS 2023). PFAS chemicals are found within several single-component refrigerants used in blends, such as R 134a, and many HFO refrigerants like R-1234yf. R-454B also contains PFAS chemicals because it is a blend of R-32 and R-1234yf. Currently, five countries in Europe are proposing a ban on refrigerants containing PFAS which would ban R-454B from use (Cooling Post 2023). R-32 on the other hand does not contain any PFAS chemicals and would be excluded from this ban.

Training and Code requirements for A2Ls.

The HVAC industry needs to be trained and educated on the proper installation, maintenance, and servicing of A2L refrigerant systems. The EPA's Technology Transitions Program provides guidance and resources for the safe and efficient use of A2L refrigerants, such as online courses, webinars, videos, and manuals.

A2L refrigerants are classified as mildly flammable and require special precautions and handling to avoid ignition and combustion risks. Modifications to the building code, fire code, and mechanical code are required to allow the use of A2L refrigerants. The 2024 International Building Code, International Fire Code, and International Mechanical Code allow the commercial and residential use of A2L refrigerants with certain restrictions and requirements, such as charge limits, leak detection, ventilation, and labeling (ICC 2024). HVAC Contractor web survey respondents were asked in 2024, whether they or anyone at their company had received training on A2L mildly flammable refrigerants. As shown in Figure *2*, only 44% of those respondents reported someone from their company having received training with eight hours of training being the average across those who reported receiving training.

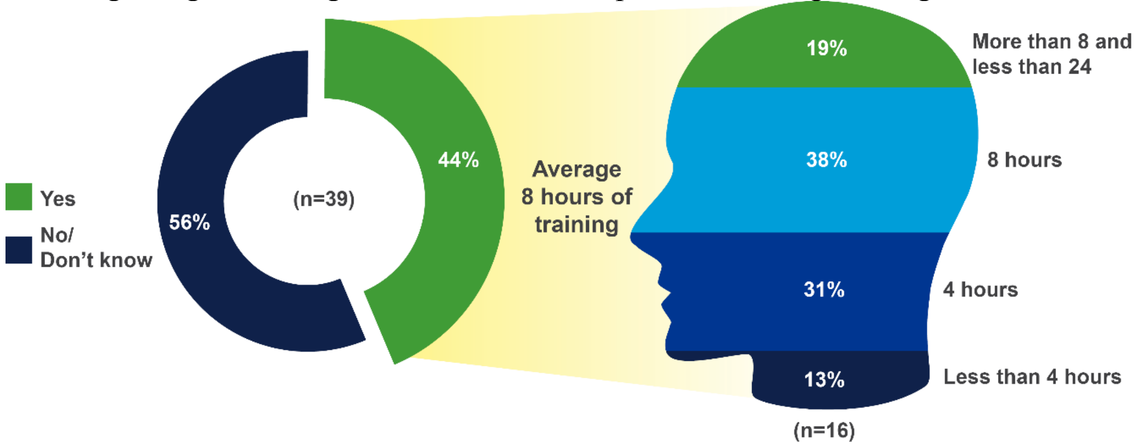

Figure 2. HVAC contractor web survey responses who received A2L training, and how many hours they received

Hydrofluoroolefin (HFO)

HFO is a type of refrigerant that has a low global warming potential (GWP) and is being used as an alternative to high-GWP refrigerants such as HFCs. HFOs are considered fourth-generation refrigerants and are being used in various applications such as air conditioning, refrigeration, and heat pumps. Some common HFO refrigerants include R-1234yf, R-1234ze, and R-1233zd. These HFOs are promoted for use in heat pump applications because they offer ultra-low GWP levels <10 and they are classified as either non-flammable or mildly flammable by ASHRAE Standard 34. Most HFO refrigerants contain PFAS chemicals and may have unknown deleterious impacts on the environment. Currently, five countries in Europe and a California Senate Bill are proposing a ban on refrigerants containing PFAS which would ban most HFOs and blends containing HFOs (Cooling Post 2023) (Skinner 2024). Refrigerant subject matter experts cite the concerns around PFAS and performance challenges as key reasons to avoid HFOs as a long-term environmentally friendly refrigerant option.

Natural Refrigerants

Natural refrigerants are an ultra-low GWP alternative with GWPs much lower than traditional refrigerants, making them a more environmentally friendly option, if performance is equivalent. Some common natural refrigerants in use today include ammonia (R-717), propane (R-290), isobutane (R-600a), and carbon dioxide (R-744). These refrigerants all have very low GWP levels. Of the common natural refrigerants listed, R-290 (propane) has the highest GWP of 4, and R-717 (ammonia) has the lowest GWP of 0. Natural refrigerants have zero ozone depletion potential, meaning they do not contribute to the depletion of the ozone layer. Natural refrigerants do not contain per and polyfluoroalkyl (PFAS) chemicals.

All natural refrigerants are single-element chemicals, meaning there are no temperature glide issues for any of the natural refrigerants available. Natural refrigerants are often cheaper than traditional refrigerants. Many natural refrigerants have similar if not improved performance compared to traditional refrigerants. For example, R-290 propane refrigerant has similar performance characteristics to R-22, R-404A, and R-134a. However, propane can achieve this performance with lower pressure drop and with less mass flow rate through the system. Table 4 shows the primary drawbacks of many natural refrigerants is either flammability or toxicity.

Table 4. Natural refrigerant barriers to adoption

Natural refrigerants	Barriers
Propane (R-290), isobutane (R-600a)	Safety: High flammability. Current 300-500 gram charge size restrictions in the U.S. limit effective hydrocarbon use to residential and smaller self-contained commercial refrigeration equipment.
Ammonia (R-717)	Safety: Toxic, mildly flammable. Limited use outside of industrial refrigeration.
Carbon dioxide (R-744)	Design: Higher system pressures due to gas properties increase system component costs, and design requirements compared to synthetic higher-GWP HFC alternatives.

Propane is emerging as a viable choice for residential and light-commercial HVAC applications in the future. The limiting factor is in building, fire, and mechanical code to increase the charge limits for the use of an A3 flammable refrigerant. In 2022, the International

Electrotechnical Committee (IEC) increased allowable charge limits for propane in residential heat pumps and air conditioners. At the International Sanitary Heating and Air Conditioning Technology Industry (ISH) 2023 in Germany, a world-leading trade fair for HVAC and Water, close to 40 manufacturers were showing propane heat pumps (Hydrocarbons21 2023). Air-to-water monobloc heat pump systems, in which all the refrigerant is hermetically sealed and contained in the outdoor unit, allow for the safe and successful use of propane in these systems. This allows for easier use of propane as a refrigerant than in the air-to-air systems in the U.S. where refrigerant lines are inside the building.

It's worth noting that the monobloc systems now emerging in Europe require an additional indoor heat exchanger that results in some loss in overall system efficiency. The extra heat transfer concern is a hurdle manufacturers are working to overcome. The larger monobloc heat pump options emerging in the European market today have been in production for less than two years. In that short period manufacturers have been introducing modified heat exchangers to optimize performance and deliver full capacity at temperatures down to 14 F. These monobloc systems also typically serve both space conditioning and DHW needs. With the combined DHW they also commonly feature smart controls to optimize time-of-use demand.

The May 2022 International Electrotechnical Commission (IEC) 60335-2-40 code update that increased charge limits for propane in heat pumps and ACs also allows for smaller mini-split and portable propane systems that don't require an additional heat exchanger. U.S. agencies will take time to authorize charge levels approved internationally however, which can slow down the adoption of natural refrigerants. Christina Starr, a refrigerant policy subject matter expert at the U.S. Environmental Investigation Agency, was interviewed by the authors of this paper and shared the following about the timeline for natural refrigerant adoption in the U.S.

"Propane is one of the most promising natural refrigerant solutions in HVAC. IEC standards for increased charge limits have not been approved in the U.S. yet but there is a proposal under ASHRAE 15, to allow for a 5-kilogram charge in an outdoor indirect monobloc unit. If that proposal proceeds in a timely fashion … the U.S. could start to see these units become available in 2028."

For other air-to-air systems, no immediate efforts to harmonize with increased IEC charge sizes exist. Unless immediate efforts are made to accelerate the approval process, it may be another five to ten years before natural refrigerants are widely available for heat pump applications in the U.S. market.

Contractor In-Depth Interviews

Six different California HVAC contractors were interviewed about heat pump installations and refrigerants. Four of the six contractors are company founders or owners whose companies range in size from 3 to 30 employees. Each contractor we spoke with is aware of the pending transition to A2L refrigerants, but all reported having minimal training (< 3 hours) specific to the mildly flammable refrigerants that will be mandated in 2025. Each contractor described the process they take when retiring an existing system and if they receive any incentives for recovered refrigerant. All six acknowledged that many contractors in the workforce do not use recovery machines to draw any remaining charge into a cylinder.

One HVAC contractor who works for a medium sized HVAC company operating out of the San Francisco Bay Area shared the process he believes contractors who cut corners with recovery use most. Often, he believes contractors aren't directly venting at the unit but instead drawing refrigerant into the compressor cylinder of the outdoor condensing unit. They then disconnect the compressor from the rest of the system. The compressor then goes to a scrap processing company where it will slowly leak until the compressor is compacted and processed for scrap resulting in total system loss. It should be noted this same contractor said his company always follows proper end-of-life recovery when retiring systems and Rapid Recovery (A subsidiary of the EPA-licensed A-GAS) picks up the recovered cylinders from their shop on a regular basis.

Another contractor, who is the president of a Southern California-based HVAC company, said he believes 80% of the contractors in practice are not following proper recovery procedures. He believes the lack of enforcement, the added time required for proper recovery, and the need to complete jobs in one day all contribute to this. This same contractor helped design an HVAC field service application known as Visual Service, which he claims provides the best means of tracking how much refrigerant is added or recovered from each unit that is serviced or removed.

The founder and lead technician for the HVAC company that primarily serves rural customers and specializes in heat pumps brought up several points worth noting:

Refrigerant leakage and training: "Operational leakage for heat pumps is a major concern. The industry lacks quality standards around refrigerant line set tightness. Current standards allow enough greyness, so contractors have a low bar to reach in order to call an install complete. Most HVAC field technicians have a limited understanding about what they are doing and struggle to diagnose and fix issues they encounter. There is a significant lack in proper trainings on how to interpret the results."

Natural refrigerants: One Southern California-based contractor shared that he retrofitted an older R-22[5] system at his home with R-290 Propane. He said while he knows it's a violation of many building and fire codes, he went ahead with the drop-in retrofit because it's more efficient and far better for the environment.

Recovery Equipment Incentives: One owner of a Southern California HVAC company brought up the idea of offering free recovery and refrigerant maintenance equipment to contractors who document recovery and reclamation. This contractor believed access to high-quality recovery equipment that is also compatible with digital maintenance and tracking tools is a barrier many contractors face. This contractor believes many HVAC technicians are sent out with lower-quality gauges and recovery machines that require longer recovery periods as well as longer vacuum testing periods on installs. Giving contractors access to better equipment that expedites recovery time would not only increase recovery/reclamation rates but could also enable technicians to get additional remote assistance and support when troubleshooting refrigerant leaks.

Improved Refrigerant Recovery and Reclamation Opportunities

In 2024, the authors of this paper hosted representatives from two EPA-licensed reclaimers, two HVAC equipment distributors, the EPA, CARB, refrigerant policy SMEs, and four HVAC-R contractors for a virtual focus group. The group met to explore a path to enable energy efficiency programs to claim avoided GHG emissions for documented end-of-life refrigerant recovery and reclamation. One of the contractors, who is also current President of the International Heating and Air Conditioning Institute (IHACI), gave a virtual demonstration of the Visual Service smartphone application his company's technicians use when installing,

[5] A Hydrochlorofluorocarbon HCFC refrigerant with ozone depleting substances that was banned for new installations in 2010

servicing, and retiring equipment in the field. The Visual Service application's ability to document the refrigerant recovery process impressed the attendees. The Visual Service application produces documentation that includes the following:

- A video of the contractor operating the recovery machine on the retired system
- A geographic pin showing the location where the existing system was retired.
- A data tracker showing both the refrigerant in the existing system decreasing and the weight of the refrigerant being transferred to the recovery cylinder increasing.
- The type and serial number of the recovery cylinder.

The focus group participants agreed that this level of documentation combined with a bill of lading from an EPA-licensed refrigerant reclaimer showing the recovery cylinder was reclaimed, would effectively prove the refrigerant was reclaimed. In the California HVAC contractor web survey, participants were asked if compensation would motivate their business to perform and document end-of-life recovery. Knowing it may involve submitting photographic evidence of the recovery process through a mobile app, they were asked how much compensation they would need to fulfill end-of-life recovery/reclamation documentation requirements on a residential split-system. Figure 3 shows that $114 was the average amount provided by the 18 respondents (46%) who agreed to specify a dollar amount.

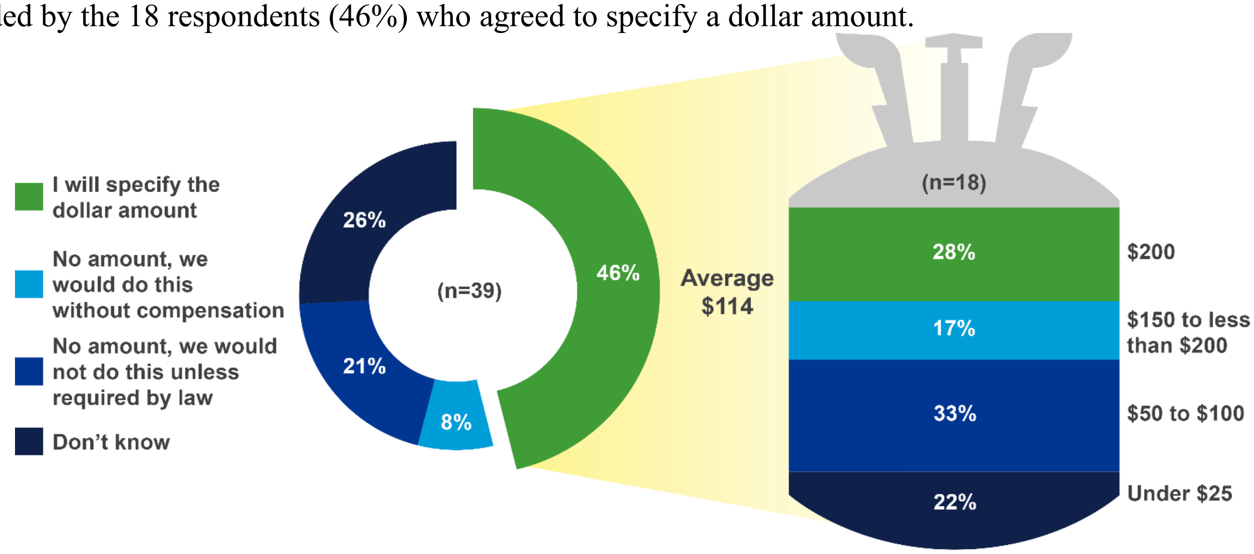

Figure 3. What compensation would be required for documenting end-of-life refrigerant recovery and reclamation?

During the focus group, refrigerant policy SMEs from the EPA and the Yale Carbon Containment Lab shared concerns that the net benefits resulting from documented end-of-life recovery need to account for several regulatory and market effects. They shared an overarching market concern that reclaimed high-GWP refrigerant does not uniformly displace demand for virgin high-GWP refrigerant. The American Innovation and Manufacturing Act subsection (h) could dramatically expand demand for reclaimed high-GWP refrigerants and there may be a need to eventually sunset avoided GHG claims for documented recovery and reclamation depending on how the market reacts to that legislation (EPA 2023). Other policy SMEs took a more practical approach reminding the group not to let perfect be the enemy of good and that end-of-life emissions are occurring at alarming rates every day. Those same policy SMEs suggested that with the right safeguards, this type of incentive or credit to key market actors could serve as a bridge to making recovery and reclamation standard practice in the workforce.

Greenhouse Gas Impacts of Heat Pump Refrigerants

The RACC (Refrigerant Avoided Cost Calculator) portion of the CPUC's RACC-FSC_V3.0 tool is designed specifically to model the carbon dioxide equivalent (CO2e) impacts due to annual refrigerant leakage and end-of-life refrigerant leakage. The RACC allows users to specify the refrigerant type and other refrigerant specific parameters for a given application. Using the California Air Resource Board's (CARB's) emission estimates by application type, the RACC provides the avoided cost in dollars over the lifetime of the appliance or measure. The output of the RACC is the net present value (NPV) costs of avoided refrigerant emissions in 2022 dollars.

Using the CPUC's current RACC-FSC_V3.0 tool the authors of this paper modeled three normal replacement (NR) electrification measure scenarios with and without existing refrigerant recovery for a 4-Ton residential central heat pump to replace a 4-Ton central air-conditioner and gas furnace system. The three electrification scenarios presented in Figure 4 include:

1. The first scenario is for a measure installed in 2024 with R-410A for both the measure and counterfactual refrigerant.
2. The second scenario is for a measure installed in 2025 with R-32 for both the measure and counterfactual or standard case refrigerant.
3. The third scenario is for a measure installed in 2028 with R-290 (propane) for the measure case refrigerant and R-32 as the counterfactual. This scenario is a hypothetical future measure pending allowance of A3 refrigerants in residential HVAC.

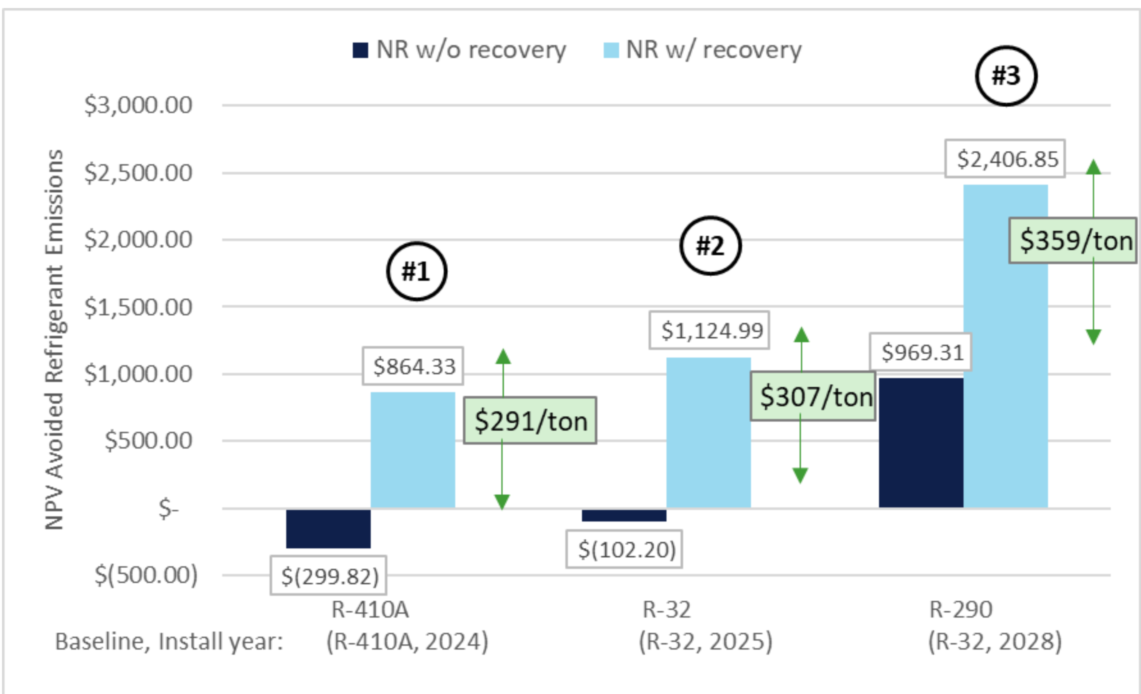

Figure 4. System lifecycle net-present-value avoided refrigerant emissions for a 4-ton residential central heat pump replacing AC and gas furnace systems. Source: DNV analysis using the CPUC's RACC-FSC_V3.0 tool.

The first scenario, involving the normal replacement of R-410A refrigerant equipment in 2024 and no end-of-life refrigerant recovery resulted in negative overall avoided refrigerant emissions of $(299.82). This was because heat pumps require more refrigerant charge than a similarly sized air-conditioning system per ton, leading to an increase in the refrigerant charge amount in the heat pump measure case. As a result, there was an increase in both annual leakage and end-of-life leakage. However, when the existing R-410A refrigerant is recovered, the avoided emissions from the recovered refrigerant alone increase the NPV cost of avoided emissions by almost 4 times.

The second normal replacement scenario of central residential HVAC equipment in 2025 involves the installation of a heat pump system with R-32 refrigerant due to the 700 GWP limit imposed by EPA regulations. Likewise, the counterfactual standard equipment also contains R-32 refrigerant as there is no standard practice for below 700 GWP refrigerants, and there are only two feasible options either R-32 or R-454B. The increased emissions impact due to the additional heat pump refrigerant charge is reduced by over 60% compared to the first scenario due to the lower GWP of R-32. When the existing equipment R-410A refrigerant is recovered, the NPV cost of avoided emissions increases by 12 times. This avoided emission cost with refrigerant recovery versus not recovering is considerably larger than the increase in scenario one. This is a result of the smaller emission impacts of R-32 relative to R-410A.

The third normal replacement scenario for a central residential HVAC replacement is for 2028, where R-290, or propane, is the hypothetical measure refrigerant, assuming the appropriate building and fire codes allow R-290 is this application. This scenario case is a central heat pump with R-290 refrigerant, replacing an R-32 air-conditioner and gas furnace system. With this example, the NPV cost impact when no existing equipment refrigerant is recovered is $969.31. This is over $1,000 greater NPV cost benefit compared to scenario two, due to the GWP differences between R-290, with a 100-year GWP of 4, and R-32, with a 100-year GWP of 675. The pre-existing equipment that was replaced would still have R-410A refrigerant, since the existing system installation year is 2013 based on the measure install year of 2028 and the DEER EUL of 15 years. When the existing R-410A refrigerant is recovered the total NPV cost benefit of avoided refrigerant emissions is $2,400.

Key Findings and Recommendations

This section presents detailed key findings and recommendations.

Refrigerant emissions will diminish heat pump net-zero-emission goals if not addressed.

Refrigerants will play a key role in determining whether heat pumps succeed in achieving net-zero-emission goals. The increased refrigerant emissions they bring as well as their impacts on system performance are far too often overlooked. The transition away from high-GWP refrigerant in HVAC heat pumps is still in the early stages. High-GWP HVAC heat pumps remain standard practice in 2024 and the next stage of lower-GWP HVAC refrigerants, R-454B and HFC-32, still have 100-year GWP levels of 466 to 675 respectively. The existing stock of high-GWP refrigerant heat pumps and air conditioners they replace will continue to leak these potent greenhouse gases for decades or until these systems are responsibly retired.

Natural Refrigerants are the most promising solution.

Research findings and refrigerant SMEs agree that natural refrigerants provide the best long-term solution for the environment. The three most common natural refrigerant categories — hydrocarbons, carbon dioxide, and ammonia — all have zero ozone-depleting properties, GWP levels below 4, no forever chemicals like PFAS, and are proven to have equal to superior performance capabilities when safety, design, and toxicity barriers are addressed.

Fund and promote natural refrigerants where and when they are permitted.

Utilities and regulators of energy efficiency incentive programs should support heat pumps containing natural refrigerants over lower-GWP synthetic refrigerants wherever natural refrigerants are permitted. Utilities and regulators should refer to the CPUC's Combined Refrigerant Avoided Cost and Fuel Substitution Calculator (RACC-FSC) to weigh the potential refrigerant greenhouse gas benefits heat pumps can achieve using low-GWP refrigerant options. Regulators should encourage all U.S. and state level codes and standards to rapidly harmonize with those in Europe and Asia.

Without aggressive intervention end-of-life refrigerant losses will continue.

In-depth interviews with HVAC contractors and climate policy experts both validate the high levels of end-of-life loss rates from CARB emissions data. Findings show the residential HVAC end-of-life emissions rates are about 80%, stemming from improper disposal, leaks during transport and storage, as well as illegal venting. Reclamation service providers offer little compensation (if any) for recovered refrigerant. Federal laws prohibiting intentional venting have existed for decades with virtually no enforcement. The prolonged lack of enforcement sent a clear message to the industry that there will be no repercussion for violating the rules. For many contractors, not following responsible recovery and disposal procedures when retiring systems is an embedded standard practice to ensure HVAC system replacements can be completed in a day and maintain profitability. This will likely remain the case until substantial monetary incentives are provided to those following proper recovery/reclamation/disposal best practices.

Allow avoided emission credit to be claimed for documented end-of-life refrigerant recovery and reclamation.

Utilities and regulators should allow avoided end-of-life refrigerant emissions to be claimed when responsible end-of-life refrigerant recovery and reclamation is completed by a licensed EPA reclaimer. This act must be documented and performed when the retired system is replaced with a new high-efficiency system containing refrigerant.

Train, compensate, and equip contractors and market actors to perform and document end-of-life refrigerant recovery/reclamation/disposal.

Web survey respondents reported they would willingly document end-of-life refrigerant recovery and reclamation on a standard size residential AC for $114. Performing this activity is worth over $700 in avoided emission TSBs.

Replace on burnout will lead to diminished performance, negative GHG impacts, and dissatisfied customers.

Far more often existing gas/AC systems are replaced when they break versus pre-emptive planning and replacement. Customers in immediate need of a new HVAC system will often prioritize getting a new system up and running fast over other important factors. Assessing and correcting the existing HVAC ductwork, properly sizing a system to heating and cooling loads, and ensuring refrigerant line sets hold a vacuum will inevitably take multiple days. When these steps are skipped or rushed performance will suffer and systems will be less reliable. Customers may regret embracing a newer technology that doesn't work as well and potentially costs more to operate.

Target accelerated replacement heat pump retrofits and combine measures.

When heat pump retrofits are combined with additional EE measures and incentives everyone benefits. Fuel substitution retrofits that also include weatherization measures, airflow optimization, and emphasize proper refrigerant line installation and testing will yield the highest combination of lifecycle energy and GHG savings. SME interviews, contractor trainings, and referenced studies categorically warn about the performance and reliability issues rushed retrofits can lead to. Targeted accelerated replacement projects will ensure customer decisions are not driven by desperation and will allow time to assess and pursue the best combination of measures. Time is a critical factor for combined measure projects to identify and secure all available incentives. Because accelerated replacement measures also claim savings using a one-third existing and two-thirds standard practice baseline, avoided operational refrigerant emissions from existing high-GWP systems will further add to total GHG benefits.

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