Cool Refrigerant Developments for a Warming World: Low GWP HVAC Refrigerant Regulations and Technologies in US and Global Markets

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ABSTRACT

Most building air conditioning and heat pump systems use refrigerant working fluids to cool and heat buildings. The most commonly used refrigerants today, known as hydrofluorocarbons (HFCs), have a high global warming potential (GWP) and will need to be replaced with low-GWP or "natural" solutions to reduce greenhouse gas (GHG) emissions, while also maintaining energy efficiency. These refrigerants contribute to GHG emissions when released to the atmosphere, which has driven governments to develop phasedown programs to support decarbonization and energy efficiency goals. This paper summarizes the state of heating, ventilation, and air conditioning (HVAC) refrigerants in the U.S. including current policies and programs, refrigerant classifications and safety standards, low and ultra-low GWP technology developments, and future opportunities to continue emissions reduction. The paper then discusses the availability and continued development of HVAC technologies using ultra-low (<150 GWP) working fluids and high efficiency solutions across the U.S., Europe, and Asia.

Introduction

Heating, ventilation, air conditioning, and refrigeration (HVAC&R) systems for building, transportation, and industrial applications commonly use the vapor-compression refrigeration cycle to move heat across different locations through the use of electrically driven compressors, fans, and other components. The vapor compression cycle operates by cyclically changing the phase state of a refrigerant working fluid between liquid, gas, and vapor at different pressures and temperatures. A wide range of air conditioner, heat pump, chiller, and other system designs rely on a refrigerant-based vapor-compression cycle to provide comfort to building occupants.

Over time, the HVAC&R industry and international leaders have recognized that certain refrigerants have detrimental impacts on the environment when released to the atmosphere due to their ozone depletion potential (ODP) or global warming potential (GWP). The HVAC&R industry is transitioning to the 4th generation of refrigerants, shown in Figure 1 below, which substantially reduce greenhouse gas (GHG) emissions and help mitigate the environmental impact of increased demand globally for comfort cooling and refrigeration. Building upon the success of the Montreal Protocol to reduce the release of 2nd generation ozone depleting chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants, government, industry, and consumer groups across the world are developing technical and policy solutions to phase down the use of 3rd generation hydrofluorocarbon (HFC) refrigerants. HFCs have zero ODP but have high GWP, which impacts global GHG emissions. Many countries use 3rd generation refrigerants today and transitioning to low GWP refrigerants will include revisiting some previously explored options, like CO_2 (R-744) and hydrocarbons (R-290, R-600a).

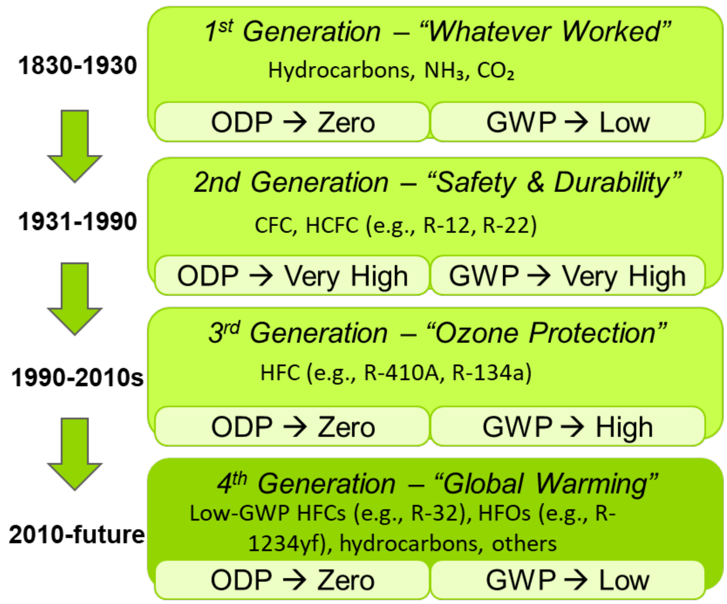

Figure 1: HVAC&R Refrigerant Transitions Over Time

Source: Calm 2008

Under pressure from U.S., European, and international policymakers, the building HVAC industry has developed solutions to reduce the environmental impacts of residential and commercial HVAC systems through the use of alternative refrigerants (e.g., R-32, R-454B, R-513A, R-1233zd(E)), as well as leakage reduction strategies using improved monitoring, analytics, and maintenance practices. HVAC systems contribute GHG emissions from two main sources, direct and indirect emissions. Direct emissions are associated with refrigerant leakage during annual operation, servicing, and end-of-life. Indirect emissions are associated with the system's electricity consumption and related power plant emissions. Federal and state refrigerant regulations target direct emissions associated with refrigerant use and leakage, whereas appliance energy efficiency standards support reductions in indirect emissions for many product categories. Each of these sources of emissions are important to keep in mind when evaluating the GHG emissions reductions in this segment, although the relative share of direct vs. indirect emissions will vary by application. Field-assembled split-system air conditioners and heat pumps have higher annual leak rates (approximately 5-15%) and will have a greater share of direct emissions compared with a self-contained window AC system with very low annual leak rate (< 2%) whose emissions will primarily be due to the electricity consumption (indirect) (CARB 2017).

HVAC manufacturers and design engineers must consider many factors when selecting low-GWP refrigerants for new equipment and systems. Specific refrigerant selection criteria include operating temperatures, system charge size, efficiency impacts, GWP, flammability, toxicity, and other thermodynamic and chemical properties. System designers must balance these characteristics and will typically favor a small number of refrigerants for any given application to reduce manufacturing and servicing complexity. Low-GWP options under consideration will typically share similar characteristics to the high GWP refrigerant targeted for replacement, except for potentially flammability and toxicity properties. While many options are promising, there are several barriers restricting the wide use of certain low and ultra-low GWP refrigerants in building HVAC applications today:

- Building, fire, and safety codes
- EPA SNAP approval
- Technician training
- Potentially higher costs of gases or systems
- Lack of awareness for industry professionals and end-users
- Availability of materials and supplies

On a national level, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 34–2022 classifies new refrigerants based on flammability and toxicity refrigerants are often referred to by their ASHRAE Standard 34 classification (e.g., A2L for refrigerants classified with lower flammability, i.e., mildly flammable). Table 1 summarizes the Standard 34 safety groupings and example refrigerants. In addition, ASHRAE Standard 15–2022 serves as the industry benchmark for safe use of HVAC&R refrigerants, UL covers safe use for specific HVAC&R equipment, and the U.S. Environmental Protection Agency (EPA) Significant New Alternatives Policy (SNAP) program specifies acceptable and unacceptable refrigerants for specific end-use applications.

Table 1. ASHRAE Standard 34 Safety Groupings and Example Refrigerants

Flammability	Toxicity	
	A – Lower Toxicity	B - Higher Toxicity
1 - No Flame Propagation (i.e., Non-Flammable)	A1 (R-410A, R-134a, R-1233zd, R-744 carbon dioxide)	B1
2L - Lower Flammability	A2L (R-32, R-454B, R-1234yf)	B2L (R-717 ammonia)
2 - Flammable	A2 (few candidates)	B2
3 - Higher Flammability	A3 (R-290 propane, R-600 isobutane)	B3

Source: ASHRAE Standard 34-2022

Current State of HVAC Refrigerants in U.S.

Refrigerant Options and Availability

Table 2 highlights various refrigerants on the market today for HVAC applications along with their corresponding classification and GWP values under Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) values. A 100-year GWP demonstrates how much energy the refrigerant will absorb thus contributing to global warming, compared to CO_2, over 100 years. Whereas a 20-year GWP demonstrates this on a 20-year timeline. The two GWP values can differ substantially for most fluorinated refrigerants. However, 100-year and 20-year GWP values tend to be the same for ultra-low GWP refrigerants since they have a near zero impact on global warming.

Table 2. Common Refrigerant Classifications and GWPs

Refrigerant	Safety Classification	Global Warming Potential (GWP) IPCC AR4	
		100-Year GWP	20-Year GWP
High GWP			
R-410a	A1	2088	4400
R-22	A1	1810	5310
R-134a	A1	1430	3810
Low GWP			
R-32	A2L	675	2530
R-454B	A2L	490	1700
Ultra-Low GWP			
R-1233zd	A1	4	1
R-290 (Propane)	A3	~20	<1
R-717 (Ammonia)	B2L	<1	0
R-744 (CO_2)	A1	1	1

Sources: R-744.com (2021), HRAI (2019)

Two of the most common refrigerants used in the HVAC industry are R-22 and R-410A. For most of the 20th century, R-22 was the most commonly used refrigerant for air conditioning and heat pumps. However, once chlorine was discovered to be a damaging chemical to the ozone layer, the use of R-22 and other hydrochlorofluorocarbons (HCFCs) that contain chlorine, were labeled as Ozone Depleting Substances (ODSs) and their uses were put under restriction by the Environmental Protection Agency (EPA). In 2010, the EPA declared that R-22 could only be used in the servicing and maintenance of equipment, and that its use in new equipment was to be discontinued. Then in 2020, the EPA banned the production and import of this refrigerant. It can only be used if it is recycled or recovered for reuse in the same system from which it is drawn.

R-410A is a hydrofluorocarbon (HFC) with an A1 classification. It is the most common refrigerant for new light commercial HVAC systems and has been largely used to replace R-22 systems. R-410A is a blend of R-32 and R-125 and is not considered an ODS; it does not have harmful effects on the ozone layer. Increased awareness of refrigerants' GWP values and the negative environmental effects associated with having a high-GWP has called for the phasedown of this refrigerant and other HFCs with high-GWP values.

The Montreal Protocol, Kyoto Protocol, and U.S. AIM Act, which will be discussed in the following section, have set goals to phase out R-410A and other high-GWP refrigerants. Two alternative refrigerants that have been coming to the market to replace these systems are R-32 and R-454B. R-32 is an A2L refrigerant with a GWP that is one third the GWP value of R-410A and R-22, deeming it a much safer refrigerant in terms of potential environment effects. This refrigerant has been on the market in HVAC systems in Japan since 2012, and in 2015, the EPA approved it for use in room air conditioners in the U.S. (Daikin 2024). Daikin has been the primary manufacturer of R-32 refrigerant and are currently developing ducted and ductless residential and light commercial products that are specifically designed for its use (Lile, 2024). R-454B is another A2L classified refrigerant. It is being manufactured by Chemours and was developed in 2018 with the first products equipped for its use launched in 2023. Several HVAC manufacturers plan to use R-454B for their North American ducted residential and light commercial products. It has similar properties and performance as R-410A refrigerant, and a higher efficiency.

As the HVAC&R industry transitions away from ODS and high-GWP refrigerants, there will be the need for redesign of many HVAC systems to ensure proper performance capabilities with the new refrigerant alternatives. The A2L refrigerants cannot directly replace R-410A so components such as compressors will need to be redesigned and optimized specifically for the corresponding A2L's use. Other important considerations for the refrigerant transition will be leak detection systems. As A2Ls are mildly flammable, it will be necessary for accurate and functioning leak detection systems to be in place to prevent and detect any refrigerant leakage. Lastly, natural refrigerants such as propane and ammonia are also being considered as viable refrigerant alternatives for this industry due to their ultra-low GWP values. These refrigerants will be discussed further later in this paper.

Industry Standards and Codes

As the industry is transitioning away from fossil fuel powered HVAC&R equipment and towards vapor compression systems that use more refrigerants, there has been an increased cause for concern with refrigerant leakage. Although the push for low- and ultra-GWP refrigerants have been an intermediary solution to avoid environmental impacts, their flammability levels have now been called into question which has led the industry to set additional safety standards to prevent and reduce refrigerant leakage. UL 60335-2-40 is one such mechanisms through which industry leaders are trying to promote the safe use of refrigerants.

To address concerns on refrigerant flammability, UL 60335-2-40 has put a limit on the amount of refrigerant charge allowed in a space based on the minimum occupied volume of the room. It also prohibits potential internal ignition sources to prevent fires that could result from leakage of flammable refrigerants. This standard also lists multiple requirements for leak detection systems that must be followed. For example, detector systems must pass safety testing per Annex LL of UL 60335-2-40, indicating-type detectors must be factory installed by the manufacturer and have a factory established set point, routine inspections should be conducted by UL, mitigation devices such as circulation fans should be controlled by the leak detectors, and self-test protocols should run every hour and have a fail-safe mode (UL Solutions 2019).

To coincide with the increased adoption of these refrigerants and updates to refrigerant standards by ASHRAE and UL, many state and local building codes have also begun to incorporate the allowance of A2L refrigerants. Some states have had to resort to a legislative approach to enable the use of A2L refrigerants given the expected timeline for building code updates in the state relative to the federal 700 GWP limit beginning 1/1/25. The Air-Conditioning, Heating, and Refrigeration Institute (AHRI) released an A2L Refrigerant Building Code Map in early 2024 that tracks the current state and local (regional or city) building codes that allow the use of A2L refrigerants (AHRI 2024).

Policies and Programs

U.S. Federal Policies

A series of international, federal, and state policies impact the selection and management of refrigerants in commercial refrigeration systems. On an international level, the Montreal

Protocol of 1987 committed countries to phasing out CFC and HCFC refrigerants to mitigate damage to the ozone layer. More recently, the 2016 Kigali Amendment to the Montreal Protocol established HFC production and consumption phasedown schedules for different categories of countries, and over 140 countries have ratified this amendment and developed their own policy strategies to meet these targets. In December 2020, Congress passed the American Innovation and Manufacturing (AIM) Act of 2020, which enables the U.S. Environmental Protection Agency (EPA) to regulate HFC refrigerants on the basis of GWP and establish HFC production/consumption limits that align with the phasedown schedules in the Kigali Amendment. This federal law will require a reduction of HFC consumption of 10% in 2022, 40% in 2024, 70% in 2029, 80% in 2034, and 85% in 2036 against a calculated baseline.

The industry is preparing now for the "big steps" in 2024 and 2029, as seen in the Figure 2, where the allowances for HFC production or import will be reduced significantly. In support of the implementation of the AIM Act, the U.S. EPA is expected to enact a series of measures to address the following:

- Limit the production and import of HFCs according to this timeline through the issuance of allowances (i.e., supply restriction)
- Delist HFC refrigerants >700 GWP for HVAC and list alternative low-GWP refrigerants for specific end-uses (i.e., demand restriction)
- Encourage the development of robust refrigerant recovery and reclaim programs (i.e., alternative supply resources)

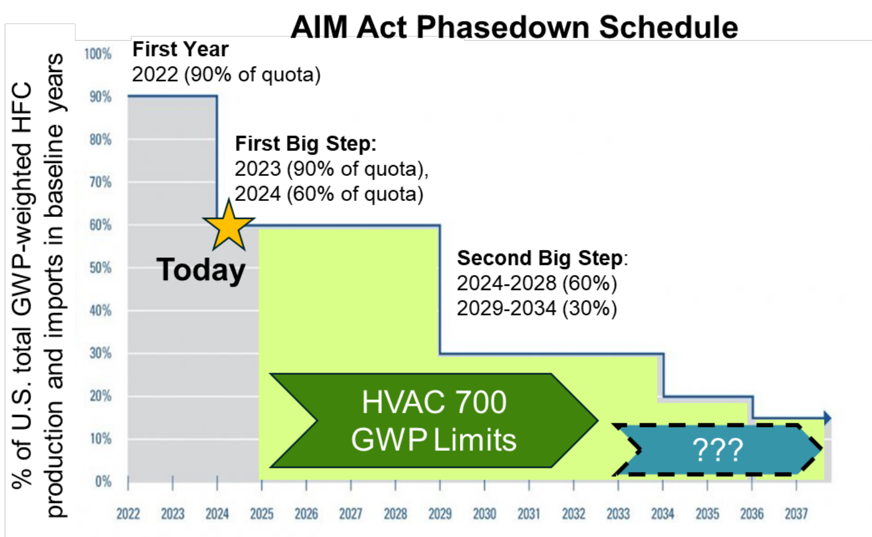

Figure 2: AIM Act Phasedown Schedule

Source: US EPA 2024, Guidehouse annotations for quotas and GWP limits

EPA has established the supply-side production and import allowances for the next several years and recently finalized the regulation for sector specific HFC restrictions in fall 2023 (EPA 2023a). The sector specific HFC restrictions outline GWP limits and dates for each major HVAC&R subsector, with the regulations primarily target new systems for new construction and major retrofit only. Most HVAC product categories will have a 700 GWP limit for products manufactured starting 1/1/2025, although variable refrigerant flow (VRF) systems have an extra year to 1/1/2026. In a subsequent amendment, EPA clarified that new HVAC systems with a GWP above 700 can be installed until January 1, 2026, so long as all components are manufactured or imported prior to January 1, 2025 (EPA 2023a). In addition, EPA also released a proposed regulation in fall 2023 that outlined different strategies to reduce leaks beyond those required for Section 608 of the Clean Air Act, and support greater refrigerant recovery and reclamation (EPA 2023b). Today, the quantity of refrigerant that is recovered from HVAC systems reaching end-of-life and reclaimed for future use is very low. EPA and other industry stakeholders are evaluating different strategies to increase recovery rates to avoid unnecessary GHG emissions and also provide sufficient reclaim supplies to offset the need for virgin refrigerant production and consumption. This regulation is under discussion currently and is expected to be finalized in late 2024.

European Policies

European HFC or F-Gas policies have historically preceded regulations in the U.S., with the EU ratifying the Kigali Amendment in 2018 and establishing a quicker phasedown timeline. Building upon earlier regulations in 2006 and 2014, EU government bodies (Parliament, Council, and Commission) in February 2024 finalized an updated F-Gas law that would move major HVAC systems to 150 GWP limits and ultimately no F-Gases over the period 2027-2035 (EU Parliament and Council 2024). Key HVAC regulations include restrictions for:

- 2027: Plug-in room, monobloc air-to-water, and other self-contained air-conditioning and heat pumps with a maximum rated capacity of 12kW (3.4 TR) that contain fluorinated gases with a GWP of 150 or more, except when required to meet safety requirements, then 750 GWP.
    - 2032: No F-Gases except for safety requirements
- 2029: Split systems of a rated capacity of up to and including 12 kW (3.4 tons) containing, or whose functioning relies upon, fluorinated greenhouse gases with GWP of 150 or more, except when required to meet safety standards.
    - 2035: No F-Gases except for safety requirements
- 2029: Split systems of a rated capacity of more than 12 kW (3.4 tons) containing, or whose functioning relies upon, fluorinated greenhouse gases with GWP of 750 or more, except when required to meet safety standards.
    - 2033: 150 GWP limit except for safety requirements

While European F-Gas regulations have started the transition towards ultra-low GWP refrigerants for the HVAC sector, there are several important distinctions to keep in mind for the transition in North America. The EU regulations contain the phrase “except when required to meet safety requirements”, which recognizes the potential challenges in moving to hydrocarbon, ammonia, CO_2, and other ultra-low GWP refrigerants that carry potential performance and safety risks. These challenges are real and require collaborative RD&D to address them similar to the current transition to A2L refrigerants. Furthermore, Much of the HP growth in Europe has been for ductless air-to-air and monobloc air-to-water HPs replacing low-temperature fossil-fuel boilers. Air-to-water HPs are self-contained systems, with lower charge, and located outdoors, which is why many products use R-290 today. Several manufacturers have announced ductless mini-split HPs R-290 (Trevisan 2022). The US market of central split-systems, packaged rooftop units, and other ducted systems have higher charge sizes, which poses issues for R-290.

In addition to concerns around the GWP of HFC refrigerants, European stakeholders are also evaluating the potential environmental and health impacts caused by chemicals known as per- and poly-fluoroalkyl substances (PFAS). PFAS include thousands of different chemical compounds and are often referred to as “forever chemicals” due to their very long lifetimes before degrading in the environment. These chemicals are found in a variety of consumer and industrial products, including firefighting foams and products treated to resist heat, water, and stains (Haggerty 2024). When released to the environment, PFAS can accumulate in soil and water, and ultimately contaminate animals and humans, which have shown to cause adverse health effects. Stakeholders in Europe and other regions have concerns around certain HFC and HFO refrigerants, most notably R-1234yf, which breakdown in the atmosphere to trifluoroacetic acid (TFA), which is a form of PFAS. TFA is also a naturally occurring chemical (EFCTC 2024), and different stakeholders hold differing opinions on the role of HFC and HFO refrigerants in observed TFA concentrations and the toxicity risks. In 2023, the European Commission proposed a broad restriction on PFAS use in Europe, which is still under discussion at this time, and if accepted would be expected to take effect in 2026 (Scott 2023).

US State Policies

In addition to federal HFC phasedown policies, California, Washington, New York, and other states are taking steps to regulate the GWP limit for refrigerants in HVAC systems. As it stands today, these state level regulations generally align with EPA’s final GWP limits. For example, California has a 750 GWP limit while EPA has a 700 GWP limit, although the primary refrigerants for HVAC applications (e.g., R-32, R-454B, R-513A, R-1233zd) would all have a GWP below 700.

Nevertheless, several states are considering an additional set of regulations to move towards ultra-low GWP refrigerants (<10 GWP) similar to the finalized EU regulations.[1] In California, SB 1206 of 2022 required the California Air Resources Board (CARB) to publish by January 2025, its plan to transition the state to ultra-low (< 10 GWP) or zero-GWP alternatives by 2035 (California 2022). CARB regulates refrigerants in California and is expected to release a draft assessment in summer 2024 in support of this law. In New York State, the Department of Environmental Conservation (DEC) released a proposed rule in late 2023 that would move the HVAC&R market towards refrigerants with < 10 GWP (20-yr) by 2034 (New York State 2023). The proposed rule would restrict the use of virgin refrigerants >10 GWP (20-yr) for new equipment and servicing starting 2027 and then a restriction on new HVAC equipment using any refrigerant greater than 10 GWP (20-yr).

Other proposed or enacted state-level regulations include high GWP refrigerant bans for HVAC equipment servicing, restrictions on PFAS products similar to proposed EU regulations, and financial incentives to encourage contractors to recover and reclaim refrigerants. California SB 1206 established bulk refrigerant bans for initial charge and servicing to encourage greater use of reclaim refrigerants. The restrictions go in effect for refrigerants with GWP >1,500 in 2030 (e.g., R-410A), and GWP >750 in 2033 (e.g., R-134a) (CARB 2024). Maine established regulations for PFAS product restriction in 2030, which does not currently cover HVAC refrigerants although the state has suggested to revisit current product exemptions in the future

[1] As noted earlier the EU regulations move towards a 150 GWP limit as a first step and then removing F-Gases, including HFOs and HFC/HFO blends, as a second step. This would in effect establish a GWP limit below 10 since the non-F-Gas refrigerants would be propane, ammonia, carbon dioxide and similar types of refrigerants.

(Maine 2024). Washington's proposed HB 2401 would establish an extended producer responsibility (EPR) strategy to boost refrigerant recovery and use of reclaim through a "tax and refund" program similar to those established in Australia and European countries (Washington 2024).

Impacts of Building Electrification

Many stakeholders support policies and programs that encourage the electrification of building space and water heating systems with heat pump technologies to reduce building GHG emissions when supplied with low carbon electricity. Nevertheless, building heating electrification will likely increase the demand for HVAC refrigerants due to several key trends. Overall, the total number of refrigerant-based HVAC systems will increase, as homes without air conditioners today add heat pump systems for space heating. In a review of manufacturer product literature for different HVAC system types, heat pumps tend to have higher charge than AC systems of similar capacity, especially for cold-climate models or variable refrigerant flow (VRF) systems. For example, 3-ton HP systems had 40-69% higher charge size than AC systems of comparable capacity and efficiency. Furthermore, colder regions moving to heat pumps will likely need a larger capacity heat pump than their existing AC system due to the larger heating loads (e.g., 4-ton CCHP vs. 2-ton AC with fossil-fuel furnace). Higher capacity systems will generally have greater refrigerant charge than lower capacity systems.

While heating electrification will likely increase refrigerant demand, the federal and state HFC phasedown policies described in this section along with low-charge product designs from manufacturers will help mitigate this issue. For example, the refrigerant demand for a R-454B and R-410A air conditioning system may be similar, but the GHG emissions impact will decrease due to the lower GWP value of R-454B. As shown in Figure 2, EPA's reduction in the production and import of HFC refrigerants will potentially drive the HVAC manufacturing industry to develop products using lower refrigerant charge. Potential low-charge design options include: a) more centrally ducted split-systems adopting "slim" designs similar to ductless mini-split AC/HPs, b) self-contained "monobloc" systems located outdoors that use hydronic loops to transfer heat with the indoor air handlers, and c) "hybrid" designs, such as VRF systems, that have a centralized refrigerant-to-water heat exchanger that distributes conditioned water to terminal units and minimizes the refrigerant piping within the building. Pursuing low-charge design options would also increase the feasibility of using ultra-low GWP refrigerants, such as hydrocarbons, and these topics are further discussed in a later section.

Product Solutions and Future Trends

Product Availability of Low GWP Options

Several manufacturers offer residential and commercial HVAC products today that use low GWP refrigerants, including certain PTACs, split systems, and window/wall units. These products are more commonly used in Europe and Asia, and it is expected that the U.S. will see more availability of these products in late 2024 and early 2025 as more policies and programs push manufacturers to low GWP solutions. Europe has quickly moved towards mildly flammable A2L refrigerant R-32 in small split systems, leading many manufacturers to stop supplying R-410A units. Although the adoption of R-32 units varies throughout Europe, the European Commission R-32 achieved an 80% market share in most countries in 2019 (Cooling Post 2020).

Ultra-Low GWP Solutions

Ultra-Low GWP (<10 GWP) options are available in certain applications, but their implementation across all industries will require addressing safety, performance, and environmental challenges. Particularly, for building air conditioning and heat pumps, there are challenges with all current potential replacements, as shown in Table 3.

- With Propane, while GWP is near zero, flammability is a much larger issue than other refrigerants, as its flammability rating is "combustible" while refrigerants such as R-32 and R-454B are only "mildly flammable". This means units with propane would need additional safety features, and building codes would need to be updated to allow their use in many circumstances. Additionally, due to the slightly higher operating pressures, it cannot be dropped into systems of today, necessitating product redesign.
- Systems with ammonia will face similar issues as units with propane, but because of its high toxicity rather than flammability. Ammonia air conditioners and heat pumps would need additional safety features and updates to building codes to allow their use.
- Carbon dioxide systems do not face any flammability or toxicity issues and have an extremely low GWP value of 1. However, the biggest issue with them is system design and achieving performance standards. The high operating pressure of carbon dioxide make designing an air conditioner or heat pump with it as a refrigerant very challenging. There has been very limited development to date for HVAC applications.
- HFOs such as R-1234yf and R-1233zd do not have the safety concerns or performance issues of other ultra low GWP refrigerants, but have environmental concerns due to the PFAS, and could be subject to future federal, state, and international regulations.

Table 3. Comparative Metrics for Residential Split-System AC/HPs

Refrigerant	Refrigerant Number	GWP (20-yr)	Safety Class	Typical Operating Pressure	Performance*	Environ. Risks
Baseline	R-410A	>4,000	A1	40- 200 psi	Baseline	High GWP
Propane	R-290	0.02	A3	100-300 psi	Slightly higher	n/a
Ammonia	R-717	0	B2L	40-200 psi	Slightly higher	n/a
CO_2	R-744	1	A1	140-720 psi	Lower, esp. for cooling	n/a
HFOs	R-1234yf	1	A2L	40- 200 psi	Slightly lower	Poten. PFAS Regs.
	R-1234ze	4	A2L	40 – 200 psi	About the same	

*relative performance compared to today's HFC refrigerants

While this list is not exhaustive of all potential ultra-low GWP refrigerants, it is clear that there is not a clear solution at this point which alleviates concerns for the wide range of building HVAC applications and system designs.

Development of Natural Refrigerant and Ultra-Low GWP Systems

Carbon dioxide (R-744) technologies in different form factors are seeing significant interest across US and Europe as an ultra-low GWP solution where hydrocarbon, ammonia, and other natural refrigerants may not be a realistic solution for the reasons discussed in previous paragraphs. There are several products either in the development, demonstration, or commercialization phase that utilize carbon dioxide as the working refrigerant. Table 4 describes four specific CO_2 heat pump products and their associated maturity.

Table 4. R-744 Heat Pumps for HVAC Applications

Company	Product Type	Description	Maturity
Harvest	Hydronic Heat Pump	Whole home space and water heating that can connect with low temp radiators or air handlers with hydronic coils for space heating and uses a storage tank for water heating. Cooling is provided through separate AC/HP or night cooling.	Commercially available in the U.S in select markets
Dalrada	Hydronic Heat pump	Combustion-free heat pumps utilizing carbon dioxide that provide both heating and cooling capabilities and increase efficiency by capturing and reusing thermal energy	Late-stage development
TripleAqua	Hydronic Heat pump	Provides heating, cooling, and hot water for medium and large residential and commercial buildings	Late-stage development
Fenagy	Water-sourced and Air-sourced Heat Pumps	Used for applications such as district heating or heating of larger buildings, but are also suitable for industrial processes, the food industry, green houses, data centers, logistics centers, offices, hospitals and HVAC in general	Product development and demonstrations in Europe

Sources: Harvest (2024), Dalrada (2024), R744 (2022), Fenagy (2024)

In 2010, two Chinese manufacturers, Meizhi and Midea, started a demonstration project to switch R-22 compressors and split AC units to R-290. The project was completed by the end of 2013, resulting in two types of compressors and AC units available for mass production that met national and international performance standards. Safety measures were implemented during the conversion to address R-290's flammability, including modified products, tools, parts, equipment, procedures, staff training, and marketing materials. The project's success has prompted other Chinese manufacturers to invest in similar conversion activities (EPA 2016).

Split ACs utilizing propane as a low GWP alternative refrigerant are commercially accessible in Chinese and Indian markets and make up approximately 2% of annual split AC sales in India. However, their adoption is limited in other regions due to building codes and standards over flammability concerns. In Europe, the European Commission has proposed transition the ductless mini-split market away from all F-Gases, see European Policies section for more details, where propane stands as a feasible option to meet these requirements if the proposal is approved (Cooling Post 2022).

In Europe, one potential solution to highly flammable refrigerants has been to use them in self-contained hydronic systems, such as monobloc air-to-water heat pumps. The benefit of these systems is to contain the flammable refrigerant outside the building in a self-contained package. Air to water heat pumps then use a hydronic distribution system to cool and heat spaces. While this is an option for buildings with existing hydronic systems or new constructions, many existing air source systems could not be replaced without significant remodeling of the building structure or utilizing a hydronic air handler in a centrally ducted home. However, this type of solution is not limited to just propane – self contained systems with hydronic distribution could theoretically use any flammable or toxic refrigerant.

Non-Vapor Compression Technologies

Table 5 highlights a range of non-vapor compression ("NVC") technologies, which do not use the traditional refrigerant-based vapor compression cycle to operate. Instead, these technologies utilize specialized properties of certain materials to transfer heat through different strategies, which are broadly categories as solid-state, electro-mechanical, and thermally activated systems. Many of these types of NVC technologies have multiple ongoing research efforts to develop the technology into a viable replacement for vapor-compression technologies. Some companies have already developed products using these NVC technologies, which are available on the market today.

- Airgreen and Mojave Energy Systems have both introduced liquid desiccant air conditioners (BMIL Technologies, 2024) (Mojave, 2024).
- Magnotherm has released a magnetocaloric beverage refrigerator (Alston, 2023).
- Tarnoc has developed a Brayton Cycle heating system (Wassink, 2021).
- Blue Heart Energy has produced a working thermoacoustic heat pump (Bellini, 2022).

While there remain challenges for full commercialization, such as cost and efficiency, the number of ongoing research efforts and working products is promising.

Table 5. Key NVC Technology Categories

Technology Option	Brief Description
Solid-State	
Magnetocaloric	Magnetocaloric technology operates on the magnetocaloric effect, a phenomenon in which a paramagnetic material exhibits reversible temperature change when exposed to a changing magnetic field.
Ionocaloric	Material phase change transformation caused by the addition or removal of ions on the material.

Technology Option	Brief Description
Electrocaloric	The electrocaloric effect is a phenomenon in which a dielectric material exhibits reversible temperature change when exposed to a changing electric field.
Thermoelectric	Under an applied voltage, thermoelectric materials generate a temperature difference that can provide space conditioning.
Electro-Mechanical	
Elastocaloric	Using the unique properties of shape memory alloys (SMA), thermoelastic cooling systems stress and release a SMA core that absorbs heat from, or rejects heat to, its surroundings.
Barocaloric	Material phase change transformation caused by changes in pressure on the material.
Evaporative	Evaporative cooling systems use water to absorb sensible heat from airstreams, evaporating the water and thus cooling the air.
Brayton	Brayton-cycle heat pumps generate usable heating and cooling by compressing and then expanding a gaseous working fluid, which is usually air.
Electrochemical	Utilizes indirect evaporative cooling from condensation after a chemical reaction. Electrochemical cells are the drivers of the chemical reaction.
Membrane	Driven by a vacuum pump, advanced membrane heat pumps provide cooling and dehumidification and/or heating and humidification by transferring moisture across a number of membranes.
Thermoacoustic	Thermoacoustic technology uses high amplitude sound waves in a noble gas to pump heat.
Thermally Activated	
Absorption	Absorption systems use a refrigerant absorbent working-fluid pair and thermal energy source to drive a heating and/or cooling cycle.
Adsoprtion	Refrigerant vapor adheres to the surface (or within the structure) of specialized adsorbent materials. These materials release the vapor when heated to a high pressure and temperature, replacing a compressor in a heat pump cycle.
Liquid Desiccant	Liquid desiccant air conditioners consist of a primary channel that dries and cools incoming air using a liquid desiccant stream and a secondary channel that evaporatively cools a water layer using a portion of the dried air, thereby further cooling the supply air.
Solid Desiccant	Solid desiccant air conditioners dry incoming air with solid desiccant materials, thereby facilitating a secondary sensible cooling step accomplished with a different cooling technology.
Vuilleumier / Stirling	Stirling heat pumps compress and expand a gaseous refrigerant to produce space conditioning by oscillating the working fluid between two chambers. The work for the Stirling heat-pump cycle is provided by a piston shared with a Stirling engine.

Conclusions and Next Steps

The HVAC sector has a strong history of developing innovative solutions to address technical, market, and policy issues, including several successful refrigerant transitions. As the US buildings industry faces a major transition in 2025 to low GWP refrigerants (< 700 GWP), many stakeholders recognize that further research and development is needed to investigate solutions with ultra-low GWP refrigerants (< 10 GWP or < 150 GWP), as well as low charge and low leak designs, to reach long-term GHG emissions goals. Some HVAC product categories have a clearer path than others to utilize ultra-low GWP refrigerants while also maintaining performance, efficiency, safety, and other key attributes. Therefore, government, industry, environmental, and other stakeholders should collaboratively discuss the major barriers and potential strategies to advance solutions for the more challenging HVAC products.

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