The Refrigerant-Circularity-Efficiency Nexus

Sustainability Best Practices in the HVAC Industry

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ABOUT

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I. Executive Summary

Key Takeaways

1. The Three Pillars

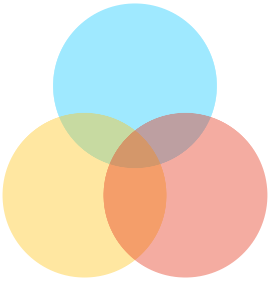
Companies in the HVAC sector seeking to strengthen sustainability should advance three pillars. First, **Refrigerant Transition** entails selecting and deploying refrigerants in strict alignment with Kigali Amendment timelines while charting a clear pathway toward low-Global Warming Potential (GWP), PFAS-free refrigerants. Second, **Refrigerant Circularity** requires embedding circular design to minimize refrigerant charge, instituting robust end-of-life recovery and reuse, strengthening data collection and traceability to prevent leakage, and building technician capacity to implement these measures. Third, **Energy Efficiency** calls for accelerating the deployment of high-efficiency products, particularly heat pumps, to reduce operational energy use.

Refrigerant Transition plans platforming medium-GWP refrigerants (R-32, R-454B) are common, yet unsustainable according to long-term policy trends. Companies should prioritize forward-looking plans including natural refrigerants (Hydrocarbons, CO2, Ammonia) to avoid costly transitions in the future. Natural refrigerants maintain similar or improved energy efficiency to manmade refrigerants, and they are not considered PFAS, which is currently a near-universal blind spot for companies.

Refrigerant Circularity practices are rarely emphasized by HVAC companies, yet are key to hitting short-term decarbonization goals while the refrigerant transition is underway. Better design can lower maintenance costs, refrigerant recovery can reduce supply costs, and reducing knowledge gaps with training and capacity building for technicians and contractors can improve customer satisfaction, all while slashing leakage.

Energy Efficiency solutions and products like heat pumps give a competitive advantage while reducing indirect emissions. Both natural refrigerant integration and anti-leak circularity practices, if done in tandem, can further increase efficiency.

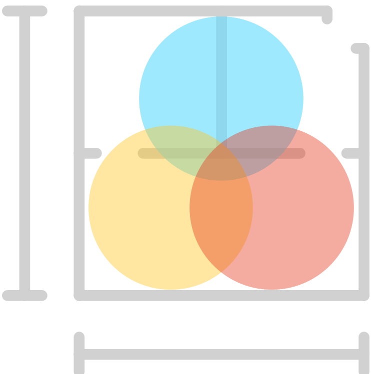
2. Finding the Nexus



The pillars of Refrigerant Transition, Refrigerant Circularity, and Energy Efficiency should be pursued as a nexus of mutually reinforcing actions, rather than as separate goals pursued in isolation, where synergies risk being lost and trade-offs overstated.

An integrated approach is essential to avoid path-dependency and the lock-in of higher-GWP or PFAS-containing refrigerants, which can strand assets, raise retrofit costs, and delay subsequent transitions to lower-impact options.

3. Aligned through Planning



Comprehensive transition plans are key to maintaining synergy among the three pillars, and should include five core aspects: strategic ambition, metrics and targets, implementation strategy, engagement strategy, and governance.

Introduction

HVAC manufacturers find themselves in a period of change prompted by attempts to regulate and mitigate the mounting impact of the industry's emissions. To address **refrigerant leakage-related emissions**, the Kigali Amendment to the Montreal Protocol went into effect in 2019 to reduce HFC production and consumption by over 80 percent by 2050.[1] Mitigation of **energy consumption-based emissions** has a more fractured policy environment worldwide, and while a range of technologies exist to improve HVAC energy efficiency, consensus on heat pump technology as a policy benchmark has increased pressure on regulators to act.

The direction of travel is clear: emissions regulations are increasing, and reducing GHG and broader environmental impact is now granting the private sector a competitive advantage. This report serves as a practical pathfinder for companies to identify best practices for GHG emissions reduction in the HVAC manufacturing and distribution industry. The analysis emphasizes existing, replicable, and scalable models of "best practice", as well as forward-looking solutions for the industry that aim to minimize environmental impact, but also to provide competitive advantages and mitigate regulatory risk as climate policy tightens. The analysis is anchored in three pillars identified as critical to sector decarbonization and sustainability and should be core to companies' transition planning and implementation strategy: (i) Refrigerant Transition, (ii) Refrigerant Circularity, and (iii) Energy Efficiency:

1. **Refrigerant Transition (leakage-based emissions):** This assesses a company's selection of refrigerants, which encompasses both their current use of refrigerants as well as their plan for refrigerant transition aligned with Kigali Amendment specifications. High performers will use a portfolio of refrigerants with low environmental impacts, or at least have explicit commitments to incorporate them into their product lines.
2. **Refrigerant Circularity (leakage-based emissions):** This assesses a company's commitments to refrigerant recovery and recyclability, but also to reduce the leakage of refrigerants from their products after sale. Given that a significant source of leakage arises from improper end-of-life disposal, the framework places particular emphasis on circular economy practices from the design phase to refrigerant recovery and reuse.
3. **Energy Efficiency (energy consumption-based emissions):** This covers non-refrigerant sources of emissions, especially energy consumption. Companies are evaluated on their efforts to transition from fossil fuel- to electricity-powered HVAC equipment, as well as on their strategies to minimize overall impacts on electricity grids post-electrification. Leaders in this criterion will prioritize high-efficiency solutions such as heat pumps or other high-performance systems that meet or exceed established standards such as ENERGY STAR.

Transition Planning: Considering the period of change arising from recent regulations and market context facing the HVAC sector, the framework also examines corporate engagement in broader sustainability initiatives. Companies with top commitments to sustainability will be actively involved in collective efforts to steer the industry towards Net Zero by collaborating with peers, value chain partners, and customers in this regard, and will have clear goals in each of the three pillars that demonstrate a sustainable roadmap. Transition planning assessment and rating initiatives such as Transition Pathway Initiative (TPI) and the CDP (formerly Carbon Disclosure

Project) can be useful to hold major players accountable, but smaller front-running companies not assessed by these frameworks can still perform well by disclosing robust transition plans in their annual and sustainability reports.

Refrigerant Transition

Given the critical role of refrigerants in driving the climate impacts of HVAC systems, it is essential to understand their contributions to global warming. A key metric for comparing these effects is Global Warming Potential (GWP), which quantifies how effectively a GHG traps heat in the atmosphere over a specified period, using CO2 as a baseline. Per- and polyfluoroalkyl substances (PFAS), commonly known as "forever chemicals," are also an indicator of environmental impact, but awareness of their prevalence in refrigerants is limited across the industry.

Most companies today are in the process of transitioning from the "Third Generation" refrigerants, valued primarily for their ozone protection properties, to "Fourth Generation" refrigerants that combine high energy efficiency with significantly lower GWP. Despite the emergence of these next-generation options, there is still global dependence on two main HFCs: R410A (residential AC and heat pumps) and R134a (refrigerators and freezers), which are both high in GWP, in particular over the shorter term, given their strong near-term warming effects.[2]

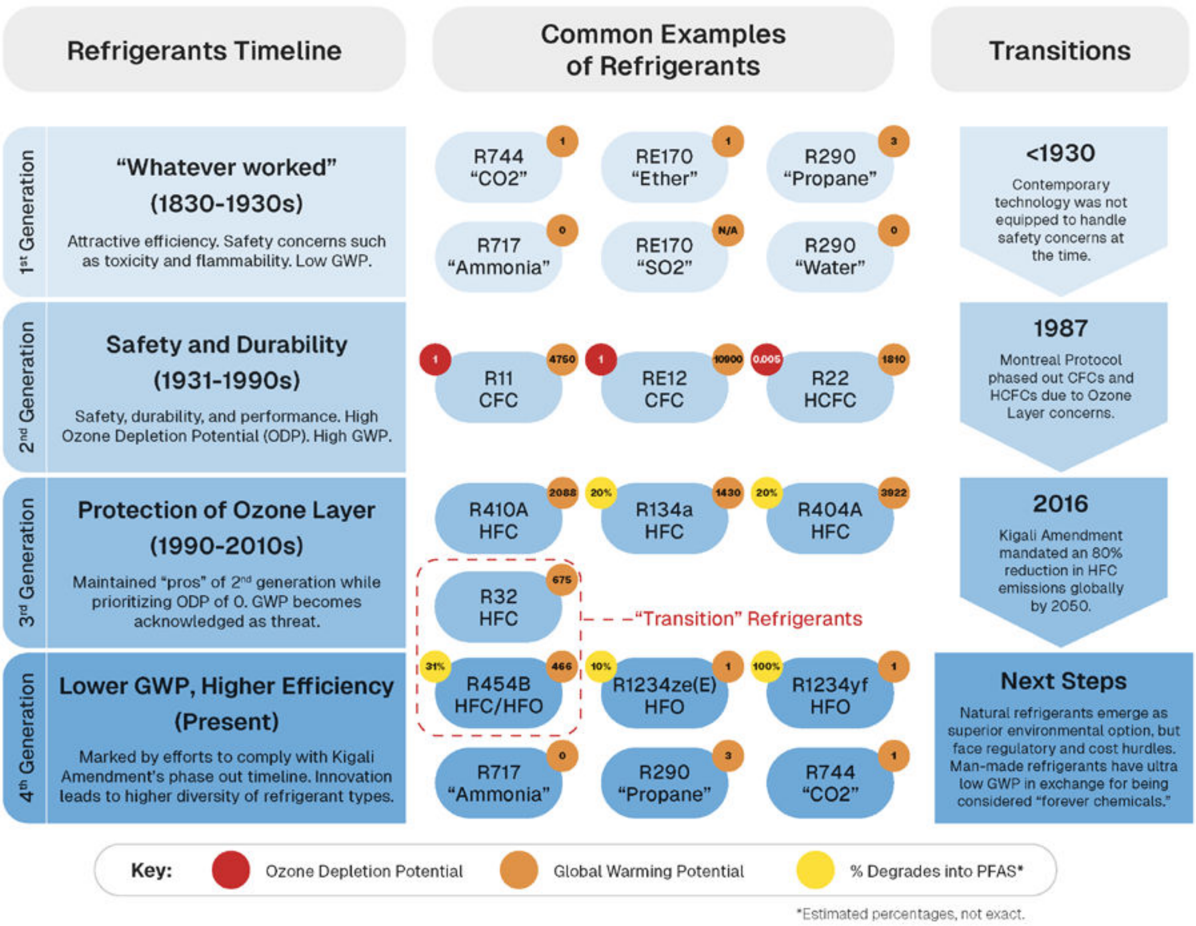


Figure 2: Refrigerant Transition Overview. Prepared by the authors. GWP values are according to the International Panel on Climate Change Assessment Report 4, except R1234ze(E) and R1234yf, which come from Assessment Report 5.

Whereas the need to transition away from "Third Generation" refrigerants is well-noted across the industry,[3] the ideal refrigerant to be transitioned *to* is less clear. Companies tout R454B's low GWP[4] and R32's relatively low GWP and non-PFAS classification,[5] whereas academics and consultants push further for lowest-impact options like CO2 and hydrocarbons.[6] As a best practices guide, this report finds natural refrigerants to be optimal in a future-looking scenario. Although they require higher upfront costs in the form of unique design accommodations and investment in capacity building for technicians, strong policy foundations in the Montreal Protocol indicate that regulations can (and likely will) continue to tighten. Adopting PFAS-free, lowest-GWP options early avoids numerous drawn-out and costly transitions in the future, thereby providing a competitive advantage for front-runner companies implementing these transitional changes.

Name	ODP	GWP 100-y	PFAS[I]	Sector	Replaces	Risk[II]	Regions
R410A	0	2088	0%	Res./ commercial AC and HPs	-	**Policy Risk:** High **Safety Risk:** No (A1) **Cost Risk:** No	**Global:** R410A and R134a still dominate residential and commercial markets. Trends for alternatives are described below: **EU:** Currently make use of R32 and R454B, but are leaders in adoption of R290 and R744. **NA:** Leans towards R454B and other HFO blends, but R32 still has presence. **Asia:** Leans towards R32, with India notably making strides toward R290 integration.
R134a	0	1430	7–20%	Mobile AC, commercial refrigeration	-	**Policy Risk:** High **Safety Risk:** No (A1) **Cost Risk:** No	
R32	0	675	0%	Res./ commercial AC and HPs	R410A R134a	**Policy Risk:** High **Safety Risk:** Low (A2L) **Cost Risk:** No	
R454B	0	466	~31%	Res./ commercial AC and HPs	R410A	**Policy Risk:** Med **Safety Risk:** Low (A2L) **Cost Risk:** Med	
R1234yf	0	1	100%	Mobile AC, component in R454B	R134a	**Policy Risk:** High **Safety Risk:** Low (A2L) **Cost Risk:** Med	
R1234ze(E)	0	1	2–10%	Industrial chillers	R134a R717	**Policy Risk:** Low (PFAS) **Safety Risk:** Low (A2L) **Cost Risk:** Med	
R290 (Propane)	0	3	0%	Res./ commercial AC and HPs, refrigeration	R410A R134a	**Policy Risk:** No **Safety Risk:** Yes (A3) **Cost Risk:** Med	
R744 (CO2)	0	1	0%	Commercial/ Industrial refrigeration, res./commercial HPs	R134a R410A	**Policy Risk:** No **Safety Risk:** No (A1) **Cost Risk:** Yes	
R717 (Ammonia)	0	0	0%	Industrial chillers	R410A R134a	**Policy Risk:** No **Safety Risk:** Med (B2L) **Cost Risk:** No	

Table 2. Summary table of relevant refrigerants and their characteristics. Prepared by the authors.[7]

I Units are listed in the percentage of the molecule which breaks down into PFAS.

II "Policy Risk" describes future policy risk. In other words, should a company be worried about its future regulation? This says nothing about its current status (e.g. flammability regulations are currently a barrier to R290 implementation, but those will only become more lenient over time). "Safety Risk" lists the flammability classifications of the refrigerants, which correspond to the following: A1 (not flammable), A2L (lower flammability), A2 (flammable), A3 (higher flammability). Ammonia is B2L because in addition to being "lower flammability," it is toxic.

Refrigerant Circularity

Regardless of which refrigerant is chosen for "future-proofing," legacy equipment designed for high-GWP HFCs like R-410A will remain in service for years; millions of units are already installed. Improper disposal and refrigerant venting at the end-of-life is one of the major contributors to leakage-based emissions in HVAC systems. To tackle this issue, manufacturers and distributors should embed circular economy practices in their operations, particularly the first two circular economy principles of the Ellen McArthur Foundation: "eliminate waste and pollution" and "circulate products and materials."[8] In the HVAC context, the former prioritizes proactive design interventions that prevent leakage and material loss before they occur; the latter emphasizes repair, reuse, remanufacture, and high-quality recovery (including certified refrigerant reclaim) across the product lifecycle. Third-party companies such as A-Gas for refrigerant recovery and FMHero for capacity building software can be looked to for partnerships or inspiration for internal practices.[9] Data limitations make it difficult to estimate exactly how much refrigerant leaks to the atmosphere each year, but the bottom line is that advancing circular systems in the HVAC industry, particularly improving end-of-life recovery that returns refrigerants to the supply chain, would drastically curtail refrigerant leakage-related emissions.

Energy Efficiency

On the side of energy efficiency, there is more of a consensus that increasing heat pump installed capacity will be highly effective on the road to net-zero. The IEA underscores the importance of widespread adoption in its NZE scenario, recommending that heat pump installed capacity increases from a 1000 GW baseline in 2022 to 3000 GW of heat pump installed capacity in 2030, 4400 GW in 2035, and 6500 GW in 2050.[10] A company looking to maximize sustainability will need to take an active approach to their rollout, however. The higher upfront cost of a heat pump can be a major barrier, not to mention that 60% of all heating purchases are "distress purchases," i.e. purchases made only because the previous HVAC equipment broke unexpectedly.[11] Increased educational materials about the energy savings of heat pumps,[12] as well as partnerships with local governments to supply residences in bulk can increase uptake in areas that would otherwise stick to their traditional HVAC systems.[13]

Heat pumps are not the perfect turn-key solution for the developing world. While it may be challenging for HVAC manufacturers to solve grid infrastructure or retrofit constraints, they can demonstrate leadership by refusing to support policy positions that delay electrification; by investing in workforce, policymaker and market education to help overcome these barriers; and even considering advancing investment on behalf of the public sector through commercial arrangements, which is a practice seen in developing countries in the mining sector.[14]

Interaction between refrigerant leakage and energy efficiency

When asked about their most pressing concerns regarding the low-GWP refrigerant transition, a 2025 survey of South Korean industry stakeholders gave their top three: (1) technical/compatibility issues, (2) cost of updating equipment, and (3) safety issues. Notably, the lowest-ranked option was "decreased energy efficiency."[15]

Evidently, the concern is less about an inherent tradeoff between GWP and efficiency, but rather the upfront cost and lead time of redesigning HVAC equipment to harness fourth generation refrigerants' efficiency. Environmentally preferable refrigerants are not intrinsically less efficient; apparent losses arise when they are used as drop-in replacements in legacy systems. When compressors, heat exchangers, charge levels, and controls are purpose-engineered for the new generation refrigerants, most (or all) of the efficiency gap is recovered. In short, efficiency is a function of system design, not refrigerant class per se; pairing climate-beneficial refrigerants with properly redesigned equipment avoids the perceived performance trade-off.

Additionally, efficient design does not inherently correlate with leak-proof design. According to data from the California Air Resource Board (CARB), the average end-of-life loss rate of heat pump refrigerants is as high as 80%. Critically, an 80% release of R-410A from a 2.5-ton capacity heat pump results in a 60% higher global warming impact than skipping the efficiency upgrade and using a conventional furnace and AC unit.[16] Moreover, CARB's 2022 emission inventory data reported that, across small, large, residential, and commercial AC units, the cumulative refrigerant loss over a system's lifetime frequently exceeds 100% of the original charge, indicating not just a single leakage event, but ongoing replenishment and repeated emissions throughout the equipment's use phase.[III] It should be noted that the fourth-highest concern in the 2025 industry survey was "lack of certified personnel."[17]

Transition Planning

The Cool Coalition, in their 2023 report Cooling Suppliers: A Stocktake on the Path to Net Zero, named their highest-ranking class of suppliers "Transformers…companies that have made strong public commitments to act on climate change and have clear, ambitious plans to decarbonise."[18] Though public commitments, disclosures, and science-based emissions reduction targets (reported to SBTi) are nice to see, front-runner HVAC manufacturers and distributors should emphasize having a credible and robust transition plan to achieve the three pillars: **refrigerant transition**, **refrigerant and equipment circularity**, and **energy efficiency**.

The framework and guidance from the Assessing Transition Plan Collective (ATP-Col) presents five elements of a plan for companies to prioritize (and stakeholders to scrutinize): **strategic ambition, metrics and targets, implementation strategy, engagement strategy, and governance.**[19] Ideally, such plans would be assessed by third party organizations such as the Transition Pathway Initiative (TPI),[20] Net Zero Tracker,[21] or InfluenceMap,[22] and indeed many of the largest industry players have personalized profiles with necessary next steps awaiting implementation. These evaluations are not always opt-in, but smaller companies can also opt into assessments by organizations such as CDP (formerly the Carbon Disclosure Project) as a launchpad for building a robust transition plan.[23] Regardless of whether third-party assessments are available, a detailed sustainability report that follows the abovementioned guidance can affirm the credibility and robustness of their transition plans to the public.

III The exception was "window/room/wall AC and packaged terminal AC units," which had 99%. Losses can exceed 100% if the equipment is refilled over its lifespan, thus it follows that the more temporary category of equipment was lower than 100% on average.

Conclusion

While replacing fossil-fuel boilers with heat pumps is one of the most effective strategies to decarbonize HVAC (particularly heating) systems, this transition must go hand-in-hand with efforts to reduce the climate impact of refrigerants. According to the IEA, heat pumps can cut greenhouse gas emissions from heating by at least 20% compared to gas boilers, up to 80% in countries with cleaner electricity, making them a cornerstone of net-zero strategies.[24] However, prioritizing heat pump deployment "regardless of refrigerant" risks locking in high-GWP substances, especially considering that many of the most commercially available heat pumps today rely on HFCs like R-410A, with 100-year GWPs exceeding 2,000 that are prone to leakage. Because HFC warming is front-loaded, rapid leakage reduction and accelerated transition to low-GWP, PFAS-free (often natural) refrigerants provide large near-term benefits—an emergency brake. Accordingly, the scale-up of heat pumps should be done in tandem with both strong investment in low-GWP, PFAS-free, refrigerant systems that offer comparable performance and efficiency; and robust refrigerant recovery and reclaim programs that successfully re-enter refrigerants into the supply chain before they vent into the atmosphere. Advancing these solutions, some of which are already present in the market, will ensure that electrification efforts are aligned with comprehensive emissions reductions across the HVAC sector.

II. Introduction

The heating, ventilation, and air conditioning (HVAC) industry is confronting a twofold challenge of escalating urgency worldwide. First, rising global temperatures due to climate change are amplifying heat stress, particularly in low- and middle-income regions, as only 15% of the 3.5 billion people living in hot climates currently have access to air conditioning. Second, as rising temperatures fuel increased demand for cooling, energy grids are experiencing significant stress trying to make up the difference.[25] By 2050, electricity demand for cooling alone in developing and emerging economies is expected to match the entire electricity consumption of the European Union in 2022, without even accounting for the rising electricity needs for heating in the context of increasing uptake of heat pumps.[26] Overall, HVAC systems, both for cooling and heating, accounted for an estimated 12% of global final energy consumption in 2020, highlighting their significant contribution to energy demand and associated emissions.[27]

Beyond emissions caused by energy consumption, HVAC systems can also leak fluorinated gases (F-gases) into the atmosphere. F-gases are used in the HVAC industry as refrigerants, which alternate from gaseous to liquid states to achieve the heating or cooling required of air conditioners, heat pumps, and other HVAC equipment.[28] The most common F-gases used in HVAC today are hydrofluorocarbons (HFCs), which can be hundreds to thousands of times more potent than carbon dioxide as a greenhouse gas (GHG) over a 100-year period, and even greater over a 20-year period, therefore significantly contributing to the HVAC industry's emissions.[29] Notably, within the European Union (EU) F-gas emissions increased by about 70% between 1990 and 2014 due to increased demand and accessibility of HVAC systems and their associated refrigerants, which has directly contributed to global warming.[30]

HVAC manufacturers and distributors thus find themselves in a period of change prompted by attempts to regulate and mitigate the mounting impact of the HVAC industry's emissions. To address **refrigerant leakage-based emissions**, the Kigali Amendment to the Montreal Protocol went into effect in 2019 to phase down HFC production and consumption by over 80 percent by 2050.[31] Mitigation of **energy consumption-based emissions** has a more fractured policy environment worldwide, and while a range of technologies exist to improve HVAC energy efficiency, consensus on heat pump technology as a policy benchmark has increased pressure on regulators to act. The EU, for example, has set a target of deploying 30 million additional heat pumps by 2030;[32] the US Climate Alliance—a coalition of 25 states and territories—aims for 20 million heat pump installations within the same timeframe;[33] and China just released their Action Plan for Promoting High-Quality Development of the Heat Pump Industry, which pledges an additional 20% in heat pump equipment efficiency through technological innovation.[34] On a global stage, the International Energy Agency's (IEA) Net Zero Emissions by 2050 (NZE) Pathway calls for a 200% increase in heat pump installed capacity between 2022 and 2030.[35] Many manufacturers have publicly endorsed these goals and initiated compliance measures, but given the pressing nature of the issue, a global stocktake is in order.

HVAC manufacturers and distributors face a high-risk context: regulatory and market pressure for transitions in both refrigerant and equipment efficiency is mounting, but the speed of innovation and diversity of alternatives and regional contexts means making the wrong decision is as easy as it is costly. Transition planning for HVAC companies in this context can be a daunting exercise of balancing solutions for refrigerant leakage-based emissions and energy consumption-based emissions. This report serves as a practical pathfinder for companies to identify best practices for

GHG emissions reduction in the HVAC manufacturing and distribution industry. The analysis emphasizes existing, replicable, and scalable models of "best practice", as well as forward-looking solutions for the industry that aim to minimize environmental impact, but also to provide competitive advantages and mitigate regulatory risk as climate policy tightens. The analysis is anchored in three pillars identified as critical to sector decarbonization and sustainability and should be core to companies' transition planning and implementation strategy: (i) Refrigerant Transition, (ii) Refrigerant Circularity, and (iii) Energy Efficiency. The sections that follow provide an overview and comparative assessment of best practices under each pillar and set clear expectations for companies to pursue continuous improvement across all three.

1. **Refrigerant Transition (leakage-based emissions):** This assesses a company's selection of refrigerants, which encompasses both their current use of refrigerants as well as their plan for refrigerant transition aligned with Kigali Amendment specifications. High performers will use a portfolio of refrigerants with low environmental impacts, or at least have explicit commitments to incorporate them into their product lines.
2. **Refrigerant Circularity (leakage-based emissions):** This assesses a company's commitments to refrigerant recovery and recyclability but also to reduce the leakage of refrigerants from their products after sale. Given that a significant source of leakage arises from improper end-of-life disposal, the framework places particular emphasis on circular economy practices from the design phase to refrigerant recovery and reuse.
3. **Energy Efficiency (energy consumption-based emissions):** This covers non-refrigerant sources of emissions, especially energy consumption. Companies are evaluated on their efforts to transition from fossil fuel- to electricity-powered HVAC equipment, as well as on their strategies to minimize overall impacts on electricity grids post-electrification. Leaders in this criterion will prioritize high-efficiency solutions such as heat pumps or other high-performance systems that meet or exceed established standards such as ENERGY STAR.

Transition Planning: Considering the period of change arising from recent regulations and market context facing the HVAC sector, the framework also examines corporate engagement in broader sustainability initiatives. Companies with top commitments to sustainability will be actively involved in collective efforts to steer the industry towards Net Zero by collaborating with peers, value chain partners, and customers in this regard, and will have clear goals in each of the three pillars that demonstrate a sustainable roadmap. Transition planning assessment and rating initiatives such as Transition Pathway Initiative (TPI) and the CDP (formerly Carbon Disclosure Project) can be useful to hold major players accountable, but smaller front-running companies not assessed by these frameworks can still perform well by disclosing robust transition plans in their annual and sustainability reports.

III. GHG Emissions in HVAC Systems: An Overview

The Life Cycle Climate Performance (LCCP) framework provides a comprehensive methodology that enables manufacturers and distributors to identify the full emissions impacts of their products by accounting for all sources of GHG emissions over the equipment's lifespan.[36] According to this framework, emissions from HVAC systems arise in two ways: **directly** and **indirectly**.

According to the LCCP, indirect emissions technically refer to both the material embodied emissions that result from manufacturing and transporting the equipment, and the emissions from the energy consumption that results from the operation of the system. This report focuses on the latter, considering that energy consumption and management typically accounts for the overwhelming majority of lifetime emissions, with one paper finding it to make up 90% of residential air source heat pump emissions, while the material embodied emissions constitute a negligible percentage of total emissions in the industry (see Figure 1).[37]

Direct (leakage-based) emissions, by contrast, happen when refrigerants leak from the equipment—escaping from the closed-loop systems designed to keep them contained—into the atmosphere. In theory, a perfectly-managed HVAC system should never produce leakage-based emissions, since, rather than functioning as feedstock, refrigerants continually alternate between liquid and gaseous states to facilitate the transfer of hot or cold air into the environment without being consumed. However, in practice, refrigerant leakage remains a persistent challenge, arising from faulty manufacturing, inadequate servicing, accidental damage, and improper disposal at end-of-life. These factors render leakage-based emissions far less predictable and more difficult to model than energy consumption-related emissions, highlighting the importance of rigorous leakage prevention and lifecycle refrigerant management in achieving sustainability improvements in the HVAC industry.[38]

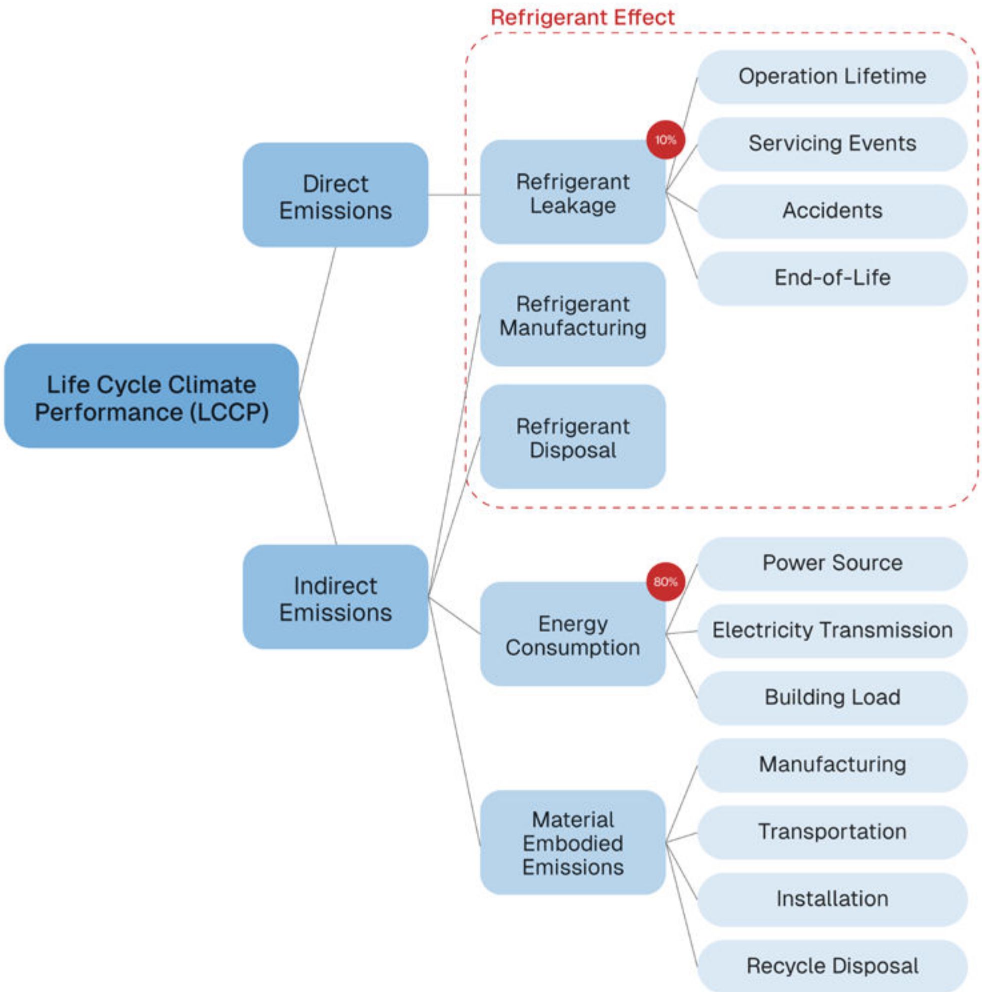


Figure 1. Visualization of lifecycle emissions from HVAC systems. Red bubbles estimate percentages of LCCP from the two major sources. Other sources range from 1–5%. Data limitations exist. Prepared by the authors.[39]

Considering the highly-developed international regulatory framework that governs leakage-based emissions and the high impact of energy consumption-related emissions on overall HVAC climate impacts, both aspects have been incorporated into this analysis. The following sections provide a concise background of both types of emissions to lend context to their corresponding specific evaluation criteria in the company assessment aspect of this report.

REFRIGERANT TRANSITION

This assesses a company's selection of refrigerants, which encompasses both their current use of refrigerants as well as their plan for refrigerant transition aligned with Kigali Amendment specifications. High performers will use a portfolio of refrigerants with low environmental impacts, or at least have explicit commitments to incorporate them into their product lines.

Given the critical role of F-gases as refrigerants in driving the environmental impacts of HVAC systems, it is essential to understand their contributions to global warming. A key metric for comparing these effects is the Global Warming Potential (GWP), which quantifies how effectively a GHG traps heat in the atmosphere over a specified period, using CO2 as a reference baseline. In this paper, GWP values indicate how many times more potent a refrigerant is at trapping heat than CO2 over a 100-year period.[40] However, it is important to note that HFCs have a very short atmospheric decay time. This means that they break down relatively quickly—over years to a few decades—so much of their warming effect is front-loaded. Consequently, on a 20-year horizon, they have a much greater warming effect, thus 20-year GWP values are substantially higher than 100-year GWP values. The practical implication for the industry is that cutting HFC emissions now can deliver large near-term climate benefits, acting as an effective "emergency brake."[IV]

Figure 2 illustrates the historical evolution of predominant refrigerant use in the HVAC industry (including F-gases), summarizing the shift from natural refrigerants to chlorofluorocarbons (CFCs), then to hydrochlorofluorocarbons (HCFCs) and subsequently to hydrofluorocarbons (HFCs), to circle back to natural refrigerants today. Most companies today are in the process of transitioning from the "Third Generation" refrigerants, valued primarily for their ozone protection properties, to "Fourth Generation" refrigerants that combine high energy efficiency with significantly lower GWP. Despite the emergence of these next-generation options, there is still global dependence on two main HFCs: R-410A (residential AC and heat pumps) and R-134a (refrigerators and freezers), which are both high in GWP.[41]

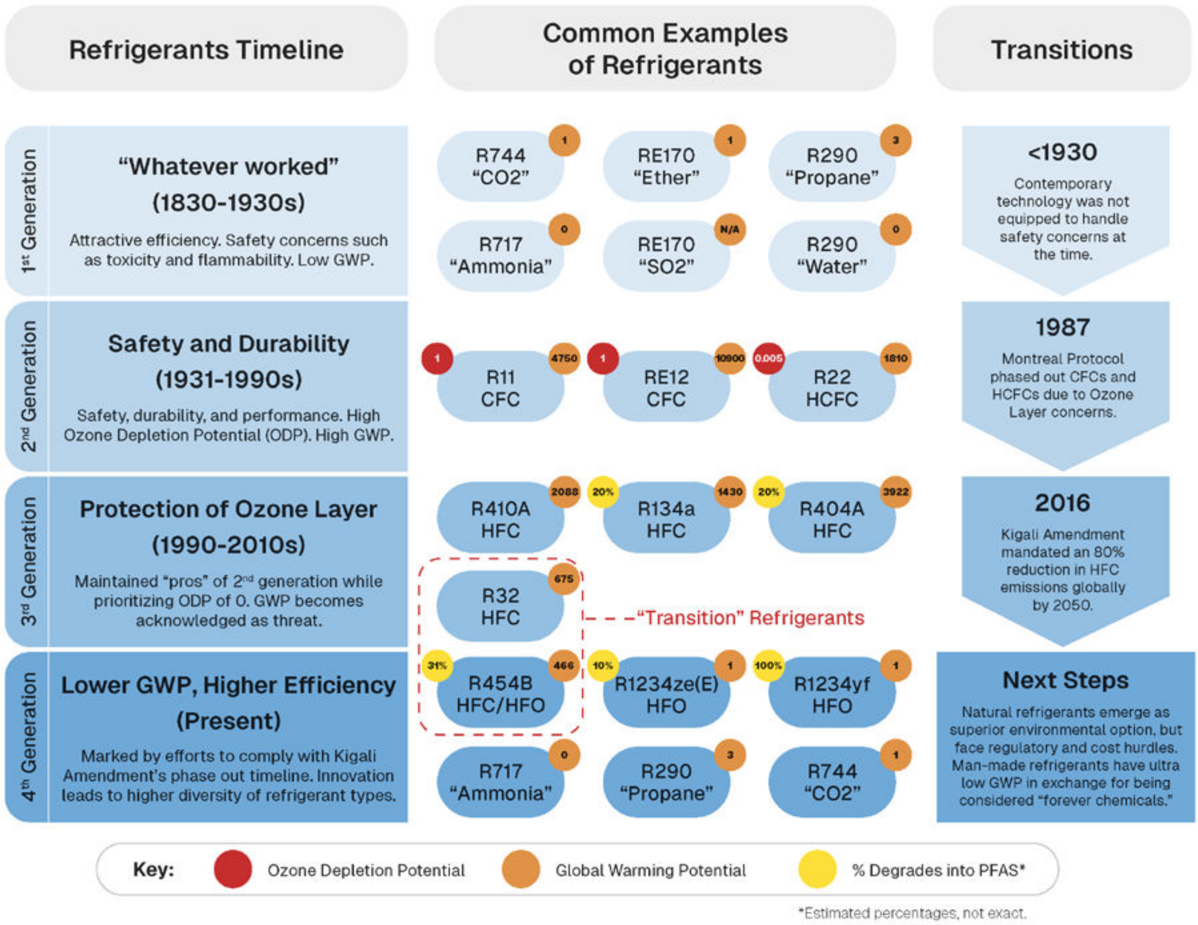


Figure 2. Refrigerant Transition Overview. Prepared by the authors. GWP values are according to the International Panel on Climate Change Assessment Report 4, except R1234ze(E) and R1234yf, which come from Assessment Report 5.

IV Note on GWP values: Unless otherwise noted, all GWP values in this report refer to the 100-year time horizon (GWP100) for ease of reference purposes.

A. Man-made Refrigerants: F-gases

Understanding the historic and current choices of refrigerants is essential for evaluating the HVAC industry's contributions to climate change through F-gases and anticipating its future regulatory and technological trajectories. Since the Second Generation of refrigerants, the HVAC industry has artificially synthesized compounds like CFCs and HFCs rather than utilizing naturally-occurring chemicals. Maintaining full control over the thermal efficiency and operational safety of their products made these engineered chemicals more attractive than First Generation (natural) options, and that trend continues today. However, the environmental drawbacks of these synthetic refrigerants soon became evident, through the high ozone depletion potential (ODP) of substances such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which catalyzed global action under the Montreal Protocol,[42] mandating their global full phase-out.

In response, the industry transitioned to Third Generation refrigerants—HFCs—which had zero ODP, thus mitigating ozone depletion. However, as the global scientific and policy communities began to understand the GWP of GHGs in the 1990s, concerns emerged regarding the high GWP of early-generation HFCs. This, in turn, prompted a new international regulation, the Kigali Amendment to the Montreal Protocol, to regulate their gradual phase-down. As shown in Info Box 1, the gradual production and consumption cuts of HFCs are based on GWP rather than on overall mass of HFCs produced. Therefore, out of the Third Generation refrigerants, R-32 has been widely adopted as a transitional option by front-runner companies in Asia, Europe and Australia, given its low GWP compared to other mainstream options (like R-410A) in its generation. That said, it remains an HFC and is therefore technically included under the Kigali Amendment's broader phase-down framework. As such, given rapidly growing demand for HVAC equipment, reliance on R-32 alone is unlikely to remain sufficient over time; forward-looking roadmaps should plan for subsequent shifts toward lower-GWP alternatives, including natural refrigerants where feasible.[V]

Info Box 1 - The Kigali Amendment Phase Down Requirements and Timeline

The Kigali Amendment to the Montreal Protocol,[43] adopted in 2016 and entered into force in 2019, aims to reduce the production and consumption of HFCs. The Kigali Amendment expands the scope of the Montreal Protocol beyond ozone protection to explicitly target climate change mitigation.

Under the Kigali framework, countries have agreed to a structured, gradual phase-down of HFC consumption and production, with specific reduction schedules tailored to different groups of countries. Developed countries (often referred to as "Article 5 non-Parties" under the Protocol) began their phased reduction in 2019, aiming for a 45% cut by 2024 and an 85% cut by 2036 compared to their baseline levels. Most developing countries, classified under Article 5 Group 1, will freeze HFC consumption levels in 2024 and work toward an 80% reduction by 2045, relative to an average baseline calculated from their 2020–2022 consumption. Meanwhile, a smaller group of countries with particularly high ambient temperatures or limited capacity (Article 5 Group 2) have slightly delayed schedules, freezing consumption in 2028 and targeting an 85% reduction by 2047.[44]

V Note on R32 insufficiency over time: Kigali prescribes an overall phase-down path (not limited to HVAC industry). Demand for refrigerants in other areas (like electric transmission switchgear, certain insulation materials or also medical equipment) is significantly higher and growing. If we add to that the increasing demand for ACs and heat pumps, R-32 most likely will not have a low enough GWP to satisfy the Kigali pathway.

This staged approach was designed to balance the urgent need to curb climate impacts with practical considerations around technological availability and economic capacity. Importantly, the Kigali Amendment also includes provisions for periodic review, technical and financial assistance (administered through the Multilateral Fund), and flexibility to accommodate countries facing unique circumstances.

For the purposes of this assessment, these phased timelines under the Kigali Amendment are key because they directly shape the regulatory context in which HVAC manufacturers and distributors operate across different regions. Given that compliance deadlines vary—with some countries required to implement reductions years or even decades earlier than others—companies may be subject to stricter HFC controls in certain markets while facing more lenient standards elsewhere. This divergence can lead to uneven sustainability practices across global operations and unfair practices toward developing countries. However, front-runner companies will be the ones that proactively adopt the stricter HFC phase-down timeline across all markets, going beyond local compliance.

The Fourth Generation of refrigerants, an industry-wide response to the Kigali Amendment, includes Hydrofluoroolefins (HFOs) and HFC/HFO blends touted as more forward-looking solutions due to their even lower GWPs. Examples such as R-1234ze and R-1234yf have been at the cutting edge of research for years, boasting the same energy efficiency and system safety advantages as HFCs, yet with an ultra-low GWP of less than 1.[45] A blend of R-32 and R-1234yf was later used to create R-454B, which has become the most common alternative for the North American market, as it has an even lower GWP than R-32. Despite their compelling attributes, a major environmental and regulatory red flag of Fourth Generation synthetic refrigerants is their classification as per- and polyfluoroalkyl substances (PFASs), extremely harmful chemicals that can remain for decades in the environment and living organisms (see Info Box 2). This issue has gained significant global attention and regulatory traction in regions such as the European Union, where policymakers are actively debating a proposed ban that would "affect virtually all new and current lower-GWP HFC/HFO refrigerant blends."[46] Even if the controversial regulation does not take the form of a full ban, the most lenient outcome of conditional continued use casts doubt on the long-term viability of HFOs and blends as a permanent solution.[47]

Out of the Third and Fourth Generations, R-32 and R-454B are two of the most popular "environmentally friendly" choices among companies today due to their significantly lower GWP compared to older Third Generation refrigerants like the widely adopted R-410A, improved energy efficiency, and wide acceptance under national regulations in the EU, US, India, and China to help meet Kigali's quota limits and phasedown targets (see Info Boxes 1 and 3). As countries seek practical ways to align with Kigali obligations without immediate technological overhauls, R-32 and R-454B are currently very popular as directly substitutable alternatives in this transitionary period.[48] However, these refrigerants should be viewed only as transition options. Although there is no immediate indication that R-32 or R-454B will be phased out in the near future, R-454B degrades into PFAS and R-32 still has a medium GWP. In contrast, the naturally-occurring Fourth Generation refrigerants explained in detail in the next section, have a more secure outlook where environmental policy is concerned. Therefore, forward-looking companies should be monitoring evolving regulations and exploring lower-GWP natural refrigerants to ensure long-term alignment with climate goals.

Info Box 2 - Per- and Polyfluoroalkyl Substances (PFASs)

The term "PFAS" describes thousands of substances, not all of which are harmful.[49] Their shared characteristic is the extremely strong bond between carbon and fluorine that makes PFASs highly durable and incredibly resistant to breaking down in the environment, often being dubbed "forever chemicals", potentially remaining for decades or even centuries in the environment and living organisms.[50]

After leaking into the atmosphere, the most common HFO refrigerants convert to a specific type of PFAS, trifluoroacetic acid (TFA), in a matter of days, then precipitate into the water cycle through rainfall.[51] For example, while HFO R-1234yf was found in 0% of samples above the European atmosphere in 2011, that number has, alarmingly, increased to 87% in 2020.[52] TFAs have been overlooked by regulators in the past due to their comparatively small size to other PFASs that are considered more harmful, but this was not taking into account the irreversibility and inevitability of their accumulation.[53]

Just as it took decades to see with certainty the harmful effects of more common PFAS, little is yet known about the long-term effects of TFAs on human and environmental health, making them difficult to regulate.[54] It is preemptively being considered a "planetary boundary threat," meeting the conditions of being disruptive to earth systems and particularly irreversible,[55] and various human health effects can be inferred from the impacts of larger substances in its PFAS group, such as ulcerative colitis, thyroid disease, elevated blood pressure during pregnancy, and testicular and kidney cancer.[56]

Europe has a longer history of PFAS regulation than the US, explaining why the latter readily adopted R-454B despite its classification as a forever chemical. In 2004, the EU implemented Regulation 850/2004 on persistent organic pollutants (POPs).[57] Although no PFASs were included under the law in 2004, it set the framework to progressively add various types in 2010,[58] 2019,[59] and 2023 amendments.[60] The EU has been in talks to implement a universal PFAS restriction since 2020,[61] with their latest proposal written in June 2025.[62] Even if it does not reach their borders right away, US manufacturers with European markets should be aware of the regulatory risk facing their use of PFASs as refrigerants.

As it relates to this report, some HFOs are more potent as PFAS than others. 100% of R-1234yf (a pure HFO which is in many of the most popular blends, and is itself becoming dominant in the mobile AC market) degrades into PFAS.[63] R-1234ze(E) is less common, but also less harmful—up to 10% of it degrades into TFA. Other notable examples currently used by manufacturers are R-454B (30% degradation), R-134a (7–20%), R-410A (0%), and R-32 (0%). Natural refrigerants, as discussed below, are not considered PFASs.

B. Natural Refrigerants: Non-F-gases

"Natural" refrigerants refer to naturally occurring substances such as CO2, hydrocarbons (e.g., propane and isobutane), and ammonia,[VI] which were originally discontinued due to the higher safety, durability, and thermodynamic performance of man-made refrigerants. However, the growing imperative to reduce GHG emissions has brought renewed attention to natural refrigerants, particularly due to their low or near-zero GWPs and zero ODPs. The three natural refrigerants mentioned above serve different purposes and should not be considered as a monolith, but their shared advantages allow them to be grouped here for simplicity. Abundant, cheap, and increasingly as efficient as synthetic refrigerants, some have even become the

VI Note: Ammonia can be both naturally occurring and artificially produced.

industry standard for some companies due to their main advantage: comparatively low environmental impacts, with low GWPs and no PFAS.[64]

Despite their environmental benefits, natural refrigerants present a range of technical and practical challenges that complicate their immediate broader adoption. The downsides to natural refrigerants vary by substance and application, ranging from a lack of convenience and compatibility with current equipment design to genuine safety concerns. Ammonia, for instance, is corrosive to copper and zinc (present in most domestic HVAC systems) and toxic to humans, making its use in small-scale HVAC more trouble than it is worth.[65] Hydrocarbons are highly flammable, which poses risks to densely populated or enclosed spaces. Although recent technological innovations have significantly mitigated these risks, prompting updated codes in some regions like Europe, many countries, particularly in the North American market, are slow to react and remain prohibitive to the growing market for hydrocarbon refrigerants.[66] Finally, CO2, while non-toxic and non-flammable, requires higher pressures than most refrigerants to reach comparable efficiency. Although technology advances have largely addressed these limitations, the need for specialized equipment remains a significant factor in cost-sensitive markets.[67]

Depending on the application, all three natural refrigerants are viable options to serve as next-generation standards in the HVAC industry. Each offers high thermodynamic efficiency and minimal climate impact. However, to match the efficiency of F-gases requires significant changes in equipment design, manufacturing processes, and technician training, alongside updated regulatory frameworks to accommodate their specific handling and safety needs.[68] In contrast, low-GWP, PFAS-free HFCs, like R-32, offer comparatively turnkey solutions that require fewer modifications to existing systems and already benefit from established supply chains, industry familiarity, and regulatory approvals. As a result, despite their environmental advantages, natural refrigerants currently face an uphill battle in gaining market dominance, particularly among manufacturers and distributors seeking lower-cost transitions. Industry players that are willing to assume the upfront cost of redesigning their systems for natural refrigerants will safeguard their product lines from regulations for years to come.

Info Box 3. Summary of Current Regulations on Refrigerant Use and PFAS

European Union

The EU's F-Gas Regulation (517/2014, revised 2024) enforces a mandatory phase-down of HFCs, aiming for a total HFC ban by 2050 –exceeding the requirements under the Kigali Amendment– through a robust quota system, strict leak controls, certification schemes, and digital tracking methods.[69] Some EU countries have introduced stricter laws than the EU F-gas Regulation. In addition, member states have proposed a REACH-based PFAS restriction that would prohibit virtually all HFC/HFO blends containing per- and polyfluoroalkyl substances.[70] Though still under review, this initiative could ban HFOs like R-1234yf and R-1234ze due to their PFAS classification.[71] Complementing these measures, the EU sets minimum energy performance standards (MEPS) for HVAC products, ensuring only equipment meeting defined efficiency thresholds can be marketed.

United States

Under the AIM Act (2020), the U.S. Environmental Protection Agency (EPA) has implemented a phasedown of HFCs, targeting an 85% reduction by 2035, compliant with the Kigali Amendment, as part of which the manufacture of new R-410A systems will no longer be allowed, starting January 1, 2025.[72] The EPA administers an allowance system, enforces equipment leak repair and reclamation protocols, and restricts high-GWP HFCs in new HVAC systems and products.[73] It has also issued rulings with the force of regulations under its Significant New Alternatives Policy (SNAP) program, which determines which substitutes are acceptable, acceptable with conditions, or unacceptable for specific uses in various sectors, banning specific high-GWP HFCs in refrigeration, foam, and aerosols.[74] While the EPA is developing its PFAS Strategic Roadmap, it has not yet banned PFAS in refrigerants,[75] and in its latest definition of PFAS in 2024, the EPA excluded TFAs from the definition.[76]

China

China has recently advanced its refrigerant governance under its Kigali commitments by adopting a comprehensive National Plan on ODS and HFC Management in April 2025. This plan details technical standards, leak detection, personnel certification, and financial tools to facilitate the phase-down of HFCs, aligning national goals with Kigali targets.[77] Complementing this, China's amended Regulation on the Administration of Ozone-Depleting Substances, effective March 2024, enforces controls on refrigerant venting, mandates recovery and destruction, and extends oversight to HFCs with clear penalties for non-compliance.[78] While China has yet to regulate PFAS or specifically address HFOs, in February 2025, the Ministry of Ecology and Environment launched a public consultation on a draft indicative list of PFAS. [79]

India

India ratified the Kigali Amendment in 2021 and will begin phasing down HFCs in 2032, targeting an 85% reduction by 2047.[80] This schedule, developed in consultation with industry, is part of India's broader climate agenda and is supported by the India Cooling Action Plan (ICAP), launched in 2019, which promotes refrigerant transition, energy efficiency, and reduced cooling demand.[81] To operationalize its commitments, the government is drafting an Action Plan for Indigenous Development to promote domestic production of low-GWP refrigerants and appliances, update safety standards, and upskill technicians.[82] India currently has no dedicated PFAS regulations.

Region	HFC Regulation	PFAS Regulation
EU	F-Gas: phase-down to 2050; exceeding Kigali	Under REACH review; potential bans on HFOs and HFC blends
U.S.	AIM Act: 85% reduction underway; SNAP bans specific HFCs; Kigali aligned	No federal refrigerant-bans yet; PFAS Roadmap; some state activity
China	Clear Kigali commitments; limited domestic enforcement	No class-wide ban; emerging PFAS concerns
India	Kigali ratified; no clear implementation plan	No PFAS regulation

Table 1. Summary of regulations per region. Prepared by the authors.

Name	ODP	GWP 100-y	PFAS[VII]	Sector	Replaces	Risk[VIII]	Regions
R410A	0	2088	0%	Res./commercial AC and HPs	---	Policy Risk: High Safety Risk: No (A1) Cost Risk: No	**Global**: R410A and R134a still dominate residential and commercial markets. Trends for alternatives are described below: **EU:** Currently make use of R32 and R454B, but are leaders in adoption of R290 and R744. **NA:** Leans towards R454B and other HFO blends, but R32 still has presence. **Asia:** Leans towards R32, with India notably making strides toward R290 integration.
R134a	0	1430	7–20%	Mobile AC, commercial refrigeration	---	Policy Risk: High Safety Risk: No (A1) Cost Risk: No	
R32	0	675	0%	Res./commercial AC and HPs	R410A R134a	Policy Risk: High Safety Risk: Low (A2L) Cost Risk: No	
R454B	0	466	~31%	Res./commercial AC and HPs	R410A	Policy Risk: Med Safety Risk: Low (A2L) Cost Risk: Med	
R1234yf	0	1	100%	Mobile AC, component in R454B	R134a	Policy Risk: High Safety Risk: Low (A2L) Cost Risk: Med	
R1234ze(E)	0	1	2–10%	Industrial chillers	R134a R717	Policy Risk: Low (PFAS) Safety Risk: Low (A2L) Cost Risk: Med	
R290 (Propane)	0	3	0%	Res./commercial AC and HPs, refrigeration	R410A R134a	Policy Risk: No Safety Risk: Yes (A3) Cost Risk: Med	
R744 (CO2)	0	1	0%	Commercial/ Industrial refrigeration, res./ commercial HPs	R134a R410A	Policy Risk: No Safety Risk: No (A1) Cost Risk: Yes	
R717 (Ammonia)	0	0	0%	Industrial chillers	R410A R134a	Policy Risk: No Safety Risk: Med (B2L) Cost Risk: No	

Table 2. Summary table of relevant refrigerants and their characteristics. Prepared by the authors.[83]

VII Units are listed in the percentage of the molecule which breaks down into PFAS.

VIII "Policy Risk" describes future policy risk. In other words, should a company be worried about its future regulation? This says nothing about its current status (e.g. flammability regulations are currently a barrier to R290 implementation, but those will only become more lenient over time). "Safety Risk" lists the flammability classifications of the refrigerants, which correspond to the following: A1 (not flammable), A2L (lower flammability), A2 (flammable), A3 (higher flammability). Ammonia is B2L because in addition to being "lower flammability," it is toxic.

Info Box 4. Imagining the Next Generation of Refrigerant Use

Recent scientific breakthroughs allow for the proposition of an HVAC industry without liquid refrigerants. Specifically, solid-state cooling occurs when a solid material changes temperature due to an external force upon it (e.g. a magnet, electric field, or mechanical compression).[84] This phenomenon is nothing new—in fact, cooling of the air due to atmospheric pressure is the process that forms clouds!

Solid-state cooling is attractive because it promises higher thermodynamic efficiency than vapor-compression—lowering energy use and grid stress—while eliminating fluid refrigerants and the leakage and regulatory risk that come with them. The technology, however, is still pre-commercial: performance, durability, and systems integration require further R&D, and current designs need form-factor optimization for mass deployment.[85]

Despite most startups being in the early research stages, RMI reports ideal conditions for growth. Notably, electrocaloric startup Phononic received USD 50 million in financing from Goldman Sachs,[86] while startup Pascal received USD 8 million for its uniquely energy-efficient technology.[87] Public-facing actors from NGOs and the private sector play a major role in raising awareness and connecting market-disrupting startups to financing. For example, the Refrigerant Emissions Elimination Forum (REEF) has connected Pascal to wider audiences through in-person events and webinars,[88] and Chemical and Engineering News listed Pascal as one of its "10 Startups to Watch."[89] Carrier Ventures, the investment arm of the major HVAC manufacturer, got involved by investing USD 17 million into solid-state specialist Exergyn.[90]

Despite the incipient nature of solid-state cooling technology, companies can get even further ahead of regulatory risk relating to refrigerant emissions by capitalizing on what looks to be the future of the refrigerant industry. In short, solid-state cooling looks like a promising next step in HVAC refrigeration, but its operational, economic, and supply-chain implications lie beyond this report's scope and remain a question for future research.

REFRIGERANT CIRCULARITY

This assesses a company's commitments to refrigerant recovery and recyclability but also to reduce the leakage of refrigerants from their products after sale. Given that a significant source of leakage arises from improper end-of-life disposal, the framework places particular emphasis on circular economy practices from the design phase to refrigerant recovery and reuse.

As the HVAC industry transitions toward less-potent greenhouse gases as refrigerants, persistent leakage from poor installation, faulty maintenance, and improper disposal threaten to undermine gains made in environmentally aligned refrigerants and equipment efficiency. According to data from the California Air Resource Board (CARB), the average end-of-life loss rate of heat pump refrigerants is as high as 80%. Critically, an 80% release of R-410A from a 2.5-ton capacity heat pump results in a 60% higher global warming impact than skipping the efficiency upgrade and using a conventional furnace and AC unit.[91] Moreover, CARB's 2022 emission inventory data reported that, across small, large, residential, and commercial AC units, the cumulative refrigerant loss over a system's lifetime frequently exceeds 100% of the original charge, indicating not just a single leakage event, but ongoing replenishment and repeated emissions throughout the equipment's use phase.[IX]

Leakage mitigation is as critical as refrigerant substitution in reducing HVAC-related greenhouse gas emissions. Accordingly, manufacturers and distributors should not only accelerate the transition to low-GWP refrigerants but also embed circular economy practices in their operations, particularly the first two circular economy principles of the Ellen McArthur Foundation: "eliminate waste and pollution", and "circulate products and materials."[92] In the HVAC industry, the former prioritizes proactive design interventions that prevent leakage and material loss before they occur; the latter emphasizes repair, reuse, remanufacture, and high-quality recovery (including certified refrigerant reclaim) across the product lifecycle. The following sections outline best practices for circular design, reuse and recovery, and addressing the knowledge gaps that may act as barriers towards implementation.

A. Circular Design

With the exception of ammonia, whose potent smell can serve as a warning, refrigerant leakage largely goes unnoticed in residential systems, even if performance is affected.[93] This underscores the responsibility of manufacturers and distributors to prevent these issues before they happen through proactive design approaches, as well as provide after-sales support for customers to mitigate long-term leakage. Examples of good practices include:

- Automatic leak detection sensors or alarms that will alert customers or technicians immediately. For instance, Daikin's Charge Integrity technology automatically alerts technicians about drops in refrigerant charge levels and is supported by the company's free access R-32 patent pool to aid companies (especially in the Global South) achieve adoption without asking for permission.[94]
- After-sales services to ensure that the problem of leakage is not merely passed down the supply chain. In addition to leak monitoring, Trane Technologies' Trane Link software provides step-by-step guidance for technicians.[95] It also connects to Trane's SmartCharge valve to reduce errors during refrigerant charging and maintenance.
- Harnessing of AI to aid in detecting leaks more efficiently. Hussman's Refrigeration IQ partnered with Phoenix Energy Technologies to develop an AI-driven software that reportedly decreases leakage by 30%.[96]
- Design equipment for longevity. Systems engineered for durable, high-integrity connections and fewer maintenance interventions significantly reduce opportunities for leakage during those instances. Incorporating such robust design principles has been shown to limit leaks and enhance performance over time.[97]

IX The exception was "window/room/wall AC and packaged terminal AC units," which had 99%. Losses can exceed 100% if the equipment is refilled over its lifespan, thus it follows that the more temporary category of equipment was lower than 100% on average.

B. Recovery

Data limitations make it difficult to estimate exactly how much refrigerant leaks to the atmosphere each year, but the bottom line is that advancing circular systems in the HVAC industry, particularly by improving end-of-life recovery that returns refrigerants to the supply chain, would drastically curtail refrigerant leakage-related emissions. At a 2025 REEF event, President of A-Gas Mike Armstrong estimated that of 230 million metric tons of refrigerant consumed in 2024 in the United States, only 9 million was recovered.[98] A recovery rate of less than 4% implies that what could function as a closed loop does not, sustaining concerns about ODP, GWP, PFAS, and other environmental harms, and undermining both leakage and in-use efficiency outcomes across HVAC equipment.

Improper disposal and refrigerant venting at the end-of-life is one of the major contributors to leakage-based emissions in HVAC systems. Refrigerant recovery should thus be a priority for companies to ensure the equipment they sell is properly decommissioned with its refrigerant recovered at a 100% rate, and either reclaimed, recycled, or destroyed. Recovery is the physical process of extracting refrigerant from an appliance and putting it in a container. After refrigerant is recovered, it can be:

- Destroyed: eliminated in such a way that the refrigerant cannot be vented into the atmosphere or otherwise reused.
- Recycling: cleaning for reuse by the original owner of the equipment. Requirements in regulation are not as stringent for recycling as they are for reclamation.
- Reclamation: reprocessed for sale and/or use in other equipment, usually to the standard of a regional agency. Reclamation of refrigerants has the highest circular value, lowering the demand on production of new refrigerants. This should be the priority for front-runner companies in the industry.[99]

Several countries have established robust policy frameworks from which the private sector can either learn from or integrate with. For example, Australia, Japan, and Norway have implemented comprehensive upstream-to-downstream guardrails to limit refrigerant leakage.[100] Norway and Australia levy high taxes on F-gas imports and provide rebates on returned refrigerants, incentivizing proper recovery and destruction. Japan, on the other hand, implements comprehensive legislation on refrigerant management for all sectors up and down the value chain.[101] The US AIM Act recently integrated their Emissions Reduction and Reclamation Program in 2024.[102] The EU's 2024 F-gas recast (Regulation 2024/573) explicitly makes recovery at decommissioning mandatory in Article 8 and requires certified personnel, tightening leak and reclamation controls.[103] China's 2024 revision of the Regulation on the Administration of Ozone Depleting Substances, along with other policies, brought HFCs under national control, now providing end-of-life recycling and reuse mandates.[104]

Complementing these regulatory frameworks, industry standards and certification help make recovery and reuse credible in practice. The Air-Conditioning, Heating, and Refrigeration Institute (AHRI) sets refrigerant recovery, equipment recycling, and performance rating standards.[105] The AHRI 700 sets the purity specification for reclaimed refrigerant (including test methods), enabling gas that meets this standard to re-enter the supply chain.[106] AHRI's Reclaimed Refrigerant (RECL) certification program verifies conformance to AHRI 700 among reclaimers.[107]

Even where regulations are robust on paper, enforcement remains the missing link across jurisdictions; as a result, end-of-life recovery is often left unaddressed. Regardless of the regulations in place, manufacturers, distributors, and end-users must take the lead in promoting responsible repair, reuse, remanufacture, and especially high-quality recovery at end-of-life for HVAC equipment and refrigerants to ensure enforcement. Examples of good practices include:

- Buy-back and take-back programs, where manufacturers ensure equipment is discharged and disposed of properly. Recently, Trane piloted a chiller buy-back program in Dubai that allowed customers to exchange their old equipment for more efficient systems.[108]

- Refrigerant reclaim programs, usually in conjunction with take-back programs, utilize the end-use refrigerants in old machines for new products. Daikin's Loop program is an excellent example of this circularity in practice. The company accepts refrigerant from any brand, reclaims it in a way that fits AHRI standards, and reuses it for their Loop systems.[109]

- Similarly, the A-Gas[110] business model centers on the efficient recovery, reclamation, and re-certification of refrigerant gases. Upon entering new markets, A-Gas typically establishes itself as an F-gas (refrigerant) recovery provider, collecting refrigerants from decommissioned systems to build an inventory of used gases. These gases—originally produced or imported by others—are then processed, purified to AHRI-700 standards, and resold with technical and compliance support. In doing so, A-Gas transforms end-of-life refrigerants into valuable circular inputs, offering a scalable model for emissions reduction without reliance on virgin production.

- Cooling- and heating-as-a-service models, which return ownership back to the HVAC company after the customer no longer needs it. These programs can be especially effective for low-income households that cannot afford the upfront cost of installation or frequent maintenance. For example, Daikin launched a joint venture with the University of Tokyo, which offers daily rental of AC in Tanzania for as low as USD 1.20 per day.[111] In a country where 7 out of 10 ACs sit unused due to the cost of repairs and poor energy efficiency, the option to pay a low price for high-efficiency Daikin products is a rare but powerful dual-solution to the issue of e-waste (by guaranteeing the return of the equipment to the original manufacturer, who can properly dispose of it) and cooling access in the global south.[112]

C. Knowledge Gaps

Technicians are often inadequately trained to deal with issues of leak repair and prevention along the HVAC system lifecycle, including during its transportation, installation, maintenance, recovery, and disposal, especially in the rapidly-evolving HVAC industry. In an interview with the American Council for an Energy-Efficient Economy, one technician stated: "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."[113] Ideally, mandatory continuing education requirements would be enforced by law,[114] but companies can ensure the compliance of their own technicians in the absence of a stringent regulatory environment. Examples of good practices include:

- First-party trainings and workshops planned around current events such as updated regulations. For instance, GE Appliances' Air & Water Solution's Learning Academy targets "handling A2Ls, focusing on leak detection, proper equipment use and compliance with evolving standards."[115] Moreover, Lennox's "2025 Refrigerant Transition" Resource Page provides a contractor- and customer-facing resource page with links to trainings ahead of upcoming regulatory changes.[116]

- Companies like FMHero address the issue at the other end, recognizing that outdated methods of data reporting and transparency exacerbate knowledge gaps, especially at the technician level. Their innovative mobile phone application allows technicians to streamline documentation and tracking of refrigerant levels and service records of their customers' equipment.[117] The app, free for technicians, diminishes the risk of falling behind on compliance with evolving regulations. Some companies fill a similar role internally; Trane uses a paperless system to document the logistics of servicing events carried out by their ~4,000 technicians so that recovery is assured.[118]

- Consumer education is also a major opportunity to increase buy-in for recovery and reclaimed refrigerants. According to a 2024 RMI report, U.S. consumers have little awareness that refrigerant recovery is legally required, which makes increased service time and costs difficult to understand.[119] In Australia, contractors physically deliver educational literature to customers about the importance of recovery for the environment. Bridging knowledge gaps not only eases recovery efforts, but paves the way for uptake of reclaimed refrigerants over virgin refrigerants.

ENERGY EFFICIENCY

This covers non-refrigerant sources of emissions, especially energy consumption. Companies are evaluated on their efforts to transition from fossil fuel- to electricity-powered HVAC equipment, as well as on their strategies to minimize overall impacts on electricity grids post-electrification. Leaders in this criterion will prioritize high-efficiency solutions such as heat pumps or other high-performance systems that meet or exceed established standards such as ENERGY STAR.

A. Energy Efficiency Metrics

As outlined above, energy consumption theoretically causes the majority of GHG emissions from HVAC systems, making equipment efficiency a central concern in assessing manufacturers' and distributors' sustainability performance. Higher-efficiency units require less electricity to deliver the same heating or cooling output, thereby reducing the emissions associated with power generation. However, unlike refrigerants, where metrics such as GWP offer standardized, internationally recognized benchmarks and regulatory frameworks, there is no universal metric for HVAC energy efficiency.[120] This is due to the significant influence of geographic and climatic variability on system performance, which makes global standardization both technically and practically challenging (see Figure 3).

The most basic measurements of energy efficiency are the Coefficient of Performance (COP) and its cooling-specific counterpart, the Energy Efficiency Ratio (EER). These metrics express the instantaneous ratio of thermal output to energy input and served as the primary global standards until the early 2000s.[121] As the industry evolved, variations of COP that included heating/cooling over an entire season, rather than just one hour, were favored to reflect variations in external temperatures. This variation became the Seasonal Energy Efficiency Ratio (SEER and SEER2) for cooling and the Heating Seasonal Performance Factor (HSPF and HSPF2) for heating in the US and EU. Other countries have adopted region-specific modifications to account for local climate conditions. For example, India's ISEER (Indian Seasonal Energy Efficiency Ratio) adjusts efficiency calculations based on its tropical temperature profiles, offering a more context-sensitive evaluation of equipment performance.[122]

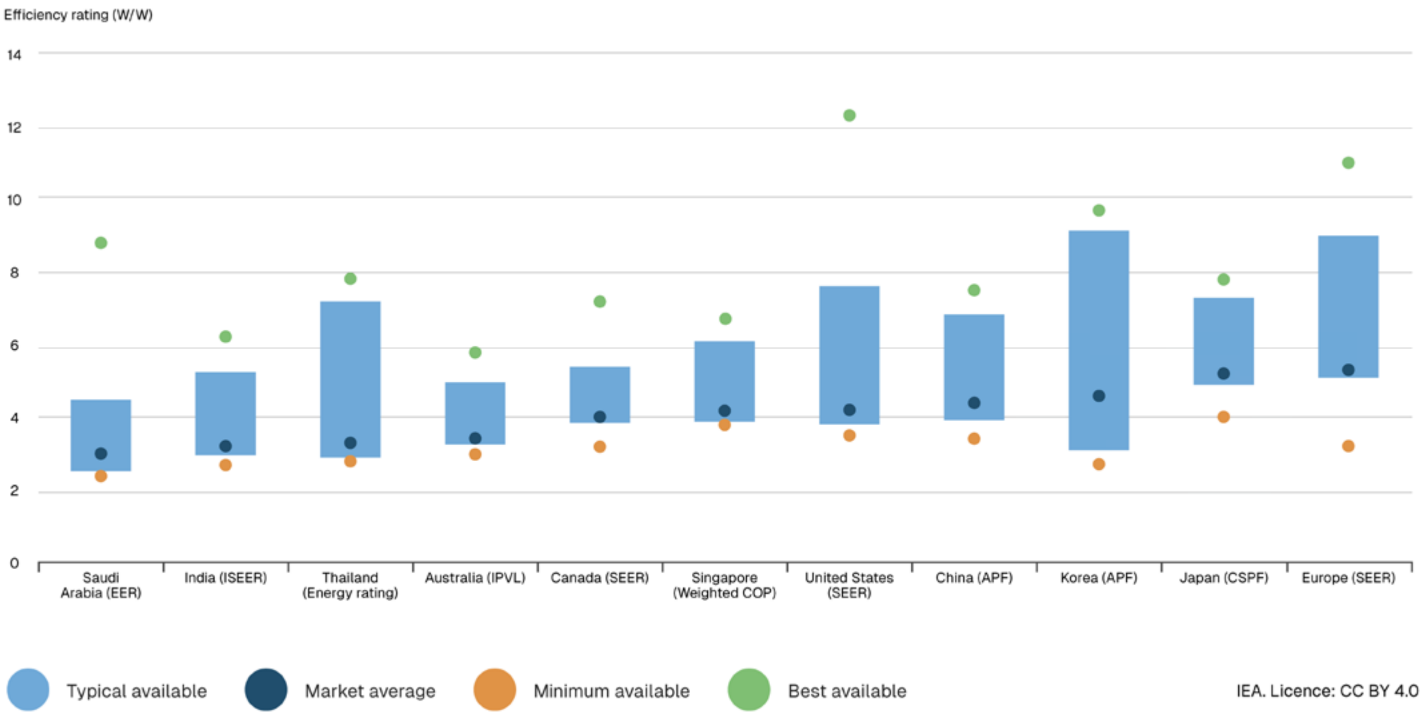


Figure 3. IEA (2020). Efficiency ratings of available AC units by regional metric as of 2020. Green dots show the best available, blue dots show the market average, and orange dots show minimum available. CSPF = Cooling Seasonal Performance Factor. APF = Annual Performance Factor. IPVL = Integrated Part Load Value. Singapore uses a Weighted COP.[123]

Because HVAC manufacturers operate across diverse regional markets—each with its own climate conditions, regulatory requirements, and efficiency standards—it is challenging to directly compare the energy performance of their products on a global scale. However, regional sustainability labels and awards can be a helpful indicator of a company's commitment to reducing energy consumption-related emissions. Table 3 provides verifiable labels, along with their measure of distinction in energy efficiency and their region(s) of operation:

Name	Countries[X]	Measure of Distinction	Description / Notes on Transparency
ENERGY STAR	USA Canada	ENERGY STAR Most Efficient 2025[124]	Provides a dataset for all Most Efficient Heat Pump certifications that is updated up to October 12, 2025[125]
Consortium for Energy Efficiency (CEE)	USA Canada	CEE Advanced Tier.[126]	More prestigious than the ENERGY STAR Most Efficient label, "quality over quantity" approach to energy-efficient product offerings. Not centrally listed or publicly searchable, requiring stakeholders to rely on manufacturers to self-disclose their participation.
Bureau of Energy Efficiency (BEE) Star Labeling	India	5 Stars[127]	Public directory called "Search and Compare," which can be filtered for 1-5 star ratings and by brand[128]
China Energy Label (CEL)	China	Level 1[129]	Publicly searchable database run by the China National Institute of Standardization (CNIS).[130]
EU Energy Label	EU	A+++ Grade.[131]	"European Product Registry for Energy Labeling" that allows searching for A+++ labels by brand.[132]

Table 3. Summary table of relevant energy efficiency labels and their characteristics. Prepared by the authors.

B. Heat Pumps

A comprehensive 2021 literature review described a "near unanimity on heat pumps' potential in mitigating GHG emissions,"[133] largely due to their bundle of conventional heating and cooling functionality into one, with major efficiency gains on the heating side. Unlike conventional furnaces, which generate heat through fuel combustion or electric resistance, heat pumps transfer ambient heat from the outside environment into the building, resulting in substantial energy savings, not to mention the shift away from fossil fuel dependence. Given their unmatched energy performance, heat pumps—particularly ground-source variants—are widely regarded as the most efficient HVAC technologies currently available.[134] The IEA underscores the importance of widespread adoption in its NZE scenario, recommending that heat pump installed capacity increases from a 1000 GW baseline in 2022 to 3000 GW of heat pump installed capacity in 2030, 4400 GW in 2035, and 6500 GW in 2050.[135] Companies that prioritize the sale and integration of heat pumps into their product portfolios are therefore likely to perform well in assessments of best practice.

X Some labels apply outside of these countries for general energy efficiency, but this table is HVAC-specific.

While heat pumps are only marginally more efficient than conventional air conditioners at cooling, the innovation vastly improves heating efficiency. Specific variations like ductless mini-split heat pumps and ground source heat pumps can achieve even higher efficiency, though they come with higher upfront costs. Moreover, thanks to the variety of types available, heat pumps are highly adaptable to diverse climates, geographical conditions and contexts. Air-source heat pumps are widely used in temperate regions due to their lower installation cost and ease of implementation, whereas ground-source (or geothermal) heat pumps and water- or exhaust-air source systems can outperform in colder or specific environmental conditions by leveraging more stable heat sources.[136] Additionally, general upgrades and innovations such as ductless,[137] inverter,[138] and zoned models can provide increased efficiency by providing greater climate control and avoiding energy losses.[139]

Heat pumps can face limitations, particularly in developing-country contexts, where they may not be universally practical. First, widespread deployment can strain underdeveloped electricity grids, potentially causing transformer overloads, voltage instability, and even outages during peak use periods.[140] Second, unlike fossil-fuel furnaces, heat pumps are completely reliant on electricity; therefore, they become inoperable in case of power outages, whereas conventional heating systems remain functional.[141] Third, in many older buildings retrofitting for heat pumps requires significant upgrades to electrical infrastructure and heat emitters, making installation costly and logistically challenging.[142] Finally, deployment is constrained by a shortage of skilled personnel, especially in emerging markets, where capacity building has not kept pace with technology diffusion.[143] While it may be challenging for HVAC manufacturers to solve grid infrastructure or retrofit constraints, they can demonstrate leadership by refusing to support policy positions that delay electrification, by investing in workforce, policymaker and market education to help overcome these barriers, and even considering advancing investment on behalf of the public sector through commercial arrangements, which is a practice seen in developing countries in other sectors such as mining.[144]

Despite these challenges, for HVAC companies, aligning with the heat pump adoption trajectory not only supports global climate goals but also expands access to high-efficiency advanced technology. By integrating these advanced systems into their business strategies, companies can play a central role in lowering energy consumption across the residential and commercial building sectors. Examples of good practices include:

- Supporting and/or pursuing internal research and development (R&D) into climate-friendly HVAC systems.[145] For instance, Trane Technologies was awarded three U.S. Department of Energy grants to pursue heat pump innovations, including ultra-high temperatures, AI-integration and better sensors, and low-GWP refrigerant use.[146] Moreover, Hoval invested USD 70 million in expanding their heat pump production to meet high demand.[147] Similarly, Viessman Climate Solutions invested USD 1.1 billion in R&D and manufacturing of heat pumps and other green solutions.[148]

- Partnering with public and private sector stakeholders to ensure stable implementation and decrease installation cost burdens on consumers. An example is how multiple manufacturers including Carrier, Lennox, Daikin, and Trane partnered with the California Energy Commission to supply the state with 6 million heat pumps by 2030.[149] Another example is Dandelion Energy partnering with Lennar to build 1,500 homes with new GSHPs in Colorado to circumvent the cost obstacle. Installing in bulk allowed customers to dilute their upfront costs and begin saving immediately on energy bills, making the proposition more attractive.[150]

- Disseminating promotional and educational materials to facilitate public understanding of heat pump benefits. The IEA reports that "distress purchases," i.e. purchases made only because the previous equipment broke unexpectedly, make up 60% of all heating equipment purchases in some countries.[151] Helping consumers understand the major innovations made in heat pump technology over the past few years can help manufacturers and distributors bring in new clients.

Transitioning from fossil-fuel boilers to heat pumps constitutes one of the highest-impact strategies for HVAC decarbonization, notably for heating; however, achieving a comprehensive sustainable cooling and heating transition further requires integrating systemic innovations that serve as complementary measures for energy consumption management in HVAC with heat pump technologies and refrigerant reforms. By prioritizing systemic solutions such as district heating and cooling networks or passive and radiant cooling strategies (see Info Box 5) alongside product-level improvements such as refrigerant selection or systems efficiency, manufacturers, policymakers, and planners can help steer the sector toward durable, low-emission infrastructure and climate-resilient urban development.

Info Box 5. Complementary Measures for Energy Consumption Management in HVAC

District Heating and Cooling Networks

Fourth and fifth generation district heating and cooling (DHC) systems offer efficient, centralized energy distribution alternatives to individual HVAC units. By sourcing heat from low-carbon generation and distributing it via insulated networks, DHC systems significantly reduce energy consumption emissions of HVAC systems at scale, particularly in dense urban settings.[152] These systems also enhance grid flexibility by aggregating energy demand, smoothing seasonal loads, and enabling integration with renewable thermal sources.[153]

Passive and Radiant Cooling Strategies

Passive cooling techniques, such as thermal mass, natural ventilation, shading, evaporative systems, and passive daytime radiative cooling (PDRC), reduce reliance on mechanical HVAC by leveraging building design and local climate features. Radiant cooling systems, including chilled-beam or embedded-surface designs, can decrease cooling energy by 30–40% compared to conventional air systems by reducing reliance on fans and conditioning air directly.[154]

These measures are necessary to complement energy consumption management in HVAC systems; however, a full analysis of all the considerations to successfully implement them in conjunction with the three pillars analyzed herein lie beyond this report's scope and remain a question for future research.[155]

C. Interaction Between Refrigerant Leakage and Energy Efficiency

When asked about their most pressing concerns regarding the low-GWP refrigerant transition, a 2025 survey of South Korean industry stakeholders gave their top three: (1) technical/compatibility issues, (2) cost of updating equipment, and (3) safety issues.

Notably, the lowest-ranked option was "decreased energy efficiency."[156] Evidently, the concern is less about a tradeoff between GWP and efficiency, but rather the upfront cost of redesigning HVAC equipment to harness fourth generation refrigerants' efficiency.

Environmentally preferable refrigerant choices are not intrinsically more or less efficient than their higher-GWP counterparts; observed efficiency gains or losses arise primarily from how equipment is redesigned to accommodate the properties of new generation refrigerants. Accordingly, there is no simple, linear trade-off in which greater climate benefit in refrigerants necessarily implies lower efficiency in the equipment. That perception typically reflects the use of lower-GWP refrigerants as drop-in replacements within legacy systems whose compressors, heat exchangers, expansion devices, controls, and charge levels were designed for a different gas. In such cases, efficiency losses are unsurprising. By contrast, when compressors and heat exchangers are purpose-engineered for lower-GWP and PFAS-free refrigerants, most or all of the apparent efficiency loss can be recovered, and in some applications performance can improve. In short, any potential inefficiency associated with new generation refrigerants is largely a design problem: with appropriate system redesign and optimization, climate-aligned refrigerants can deliver efficiency that is competitive with, and sometimes superior to, legacy HVAC.

VII. Transition Planning

The Cool Coalition, in their 2023 report Cooling Suppliers: A Stocktake on the Path to Net Zero, named their highest-ranking class of suppliers "Transformers…companies that have made strong public commitments to act on climate change and have clear, ambitious plans to decarbonise."[157] Though public commitments, disclosures, and science-based emissions reduction targets (reported to SBTi) are nice to see, front-runner HVAC manufacturers and distributors should emphasize having a credible and robust transition plan to achieve the three pillars explored in this report: **refrigerant transition, refrigerant and equipment circularity, and energy efficiency.**

The framework and guidance from the Assessing Transition Plans Collective (ATP-Col) presents five elements of a plan for companies to prioritize (and stakeholders to scrutinize): **strategic ambition, metrics and targets, implementation strategy, engagement strategy, and governance.**[158]

- Strategic Ambition: Lays out the three pillars, their goals for achieving them, and describes how that achievement avoids harming stakeholders and society while safeguarding the environment. Highlighting key assumptions and external factors are important to maintain transparency and credibility.

- Metrics and Targets: Includes all the metrics and targets the company is relying on for accounting their progress towards the pillars. Credible plans will include qualitative assessments of "locked-in" GHG emissions from their existing products (e.g. refrigerant GWPs from current product line).

- Implementation Strategy: Covers specific actions taken in business operations, products, and services to achieve the pillars while referencing its targets. Capital expenditure (CapEx), research and development (R&D), and sources of financing should be quantified, especially towards efficient systems or new refrigerants. Resulting implications for financial performance should be made clear (e.g. risk reduction for costlier transitions in the future due to new regulations).

- Engagement Strategy: Companies should describe their engagement with public sector, NGOs, civil society, industry peers, to verify their status as a driver of, not a barrier to, systemic change.

- Governance: This is a measure to ensure the implementation plan is supported by the company's internal governance structure. Supervisory bodies within the company should approve of, and be actively engaged in, the plan towards achieving the three pillars.

Though verification of companies' transition plans according to the ATP-Col framework is not yet possible, third-party assessments are helpful to better understand the gaps for improvement. For larger companies, accessible sources such as the Transition Pathway Initiative (TPI) and the Net Zero Tracker exist to independently assess the prioritization of energy transition planning and implementation,[159] weeding out red flags such as scope 3 coverage and use of carbon credits,[160] respectively. These tools have a narrow scope of 2,000 of the largest public corporations globally, so they can be trusted to hold major players accountable to those five elements mentioned above. Smaller companies, on the other hand, have a much higher burden to opt into independent assessments. One helpful tool is the CDP (formerly Carbon Disclosure Project), which serves to publicly disclose and rate information beyond targets, on metrics, planning, and engagement strategies. Robust sustainability reports should supplement CDP participation to ensure robustness and credibility on implementation strategy and governance elements as well.[161]

A key resource for assessing the engagement strategy of larger HVAC companies is InfluenceMap's LobbyMap, which scrutinizes lobbying practices, policy engagement intensity, and the alignment of partnered industry associations and coalitions.[162] They also have "disclosure scorecards" for the quality and completeness of a company's disclosures regarding lobbying and membership in associations.[163] LobbyMap uses an A–F grading scale, with "B" or above signaling that the company is aligned with the Paris Agreement. The same disclaimer for TPI and Net Zero Tracker applies to InfluenceMap: since they only report on large companies, the absence of their approval does not imply a smaller company is doing something wrong. After all, larger companies are held to a higher standard of policy engagement due to their higher influence.

Third-party assessments are not replacements for a robust and credible annual report, but rather supplemental tools to allow outsiders to better understand and compare with similar companies. Ultimately, any information shared with third-party assessors should be disclosed by the company itself and easily accessible to the public.

VIII. Conclusion

HVAC companies must be mindful of the cross-cutting nature of the ongoing refrigerant and equipment efficiency transitions when thinking about decarbonization strategies. While replacing fossil-fuel boilers with heat pumps is one of the most effective strategies to decarbonize HVAC (particularly heating) systems, this transition must go hand-in-hand with efforts to reduce the climate and environmental impact of refrigerants. According to the IEA, heat pumps can cut greenhouse gas emissions from heating by at least 20% compared to gas boilers, up to 80% in countries with cleaner electricity, making them a cornerstone of net-zero strategies.[164] However, prioritizing heat pump deployment "regardless of refrigerant" risks locking in high-GWP substances, especially considering that many of the most commercially available heat pumps today rely on HFCs like R-410A, with 100-year GWPs exceeding 2,000 that are prone to leakage. Because HFC warming is front-loaded, rapid leakage reduction and accelerated transition to low-GWP, PFAS-free (often natural) refrigerants provide large near-term benefits—an emergency brake. Accordingly, the scale-up of heat pumps should be done in tandem with both strong investment in low-GWP, PFAS-free, refrigerant systems that offer comparable performance and efficiency; and robust refrigerant recovery and reclaim programs that successfully re-enter refrigerants into the supply chain before they vent into the atmosphere. Advancing these solutions, some of which are already present in the market, will ensure that electrification efforts are aligned with comprehensive emissions reductions across the HVAC sector.

This report can be used to navigate that complexity, offering analysis anchored in three pillars for GHG emissions reduction. Long-term competitive advantage and mitigating regulatory exposure requires continuous, integrated action across the Refrigerant Transition (moving to low-impact refrigerants), Refrigerant Circularity (maximizing recovery and minimizing leakage), and Energy Efficiency (prioritizing high-performance systems) pillars.[XI] Ultimately, by adopting these scalable best practices and integrating them through a robust and transparent Transition Plan, HVAC manufacturers and distributors can increase their competitive advantages, and secure a leadership position while rising to meet the incoming global cooling demand catalyzed by climate change.

XI Self-assessments can be conducted using the rubric in Annex I.

Endnotes

1 United Nations, Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer, UN Doc. 28/1 (April 22, 2016), Art. 2(f), https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-2-f&chapter=27&clang=_en.

2 Won Young Park, Nihar Shah, and Brian Gerke, Assessment of Commercially Available Energy-Efficient Room Air Conditioners Including Models With Low Global Warming Potential (GWP) Refrigerants (Berkeley: Lawrence Berkeley National Laboratory, 2017), 4, https://escholarship.org/uc/item/01h8g7zb.l; Bukola Bolaji, "Theoretical Assessment of New Low Global Warming Potential Refrigerant Mixtures as Eco-Friendly Alternatives in Domestic Refrigeration Systems," Scientific African (2020), https://www.sciencedirect.com/science/article/pii/S2468227620303690#bbib0022.

3 Bumcheul Park, Laying the Groundwork: Accelerating the HFCs Transition and Lifecycle Refrigerant Management – An HVACR Industry Survey: Focus on the South Korean HVACR Sector (Solutions for Our Climate (SFOC), 2025), https://content.forourclimate.org/files/research/Hvzly5e.pdf?_gl=1*15193ah*_gcl_au*MTIyODc1NTg5LjE3NTcwMTg4MTA.*_ga*MTM5OTk1MjY3MS4xNzU3MDE4ODEw*_ga_3HFQS8SMJN*czE3NTcwMTg4MTAkbzEkZzEkdDE3NTcwMTg4NjEkajkkbDAkaDA.

4 "Understanding R-454B Refrigerant," Trane Technologies, https://www.trane.com/residential/en/resources/glossary/what-is-r454b-refrigerant/

5 "R-32: The Most Balanced Refrigerant for Stationary Air Conditioners and Heat Pumps," Daikin Global, https://www.daikin.com/csr/information/refrigerant/hfc32.

6 Brad Hoover, Bryan Kilgore, and Christina Torok, Refrigerants, Taking the Chill Out of Heat Pumps (American Council for an Energy-Efficient Economy (ACEEE), 2024), https://www.aceee.org/sites/default/files/proceedings/ssb24/assets/attachments/20240722160821125_d5e08544-1392-4f70-83dd-cab5934a66e5.pdf; Naeem Abas, Ali Raza Kalair, Nasrullah Khan b, Aun Haider, Zahid Saleem, and Muhammad Shoaib Saleem,, "Natural and Synthetic Refrigerants, Global Warming: A Review," Renewable and Sustainable Energy Reviews, No. 90 (2018): 557-569, https://www.sciencedirect.com/science/article/abs/pii/S1364032118301977.

7 "Technology Transitions GWP Reference Table," United States Environmental Protection Agency, https://www.epa.gov/climate-hfcs-reduction/technology-transitions-gwp-reference-table#:~:text=Blends%20of%200%25%20to%20100,HFC%2D; Danfoss, Refrigerant Options Now and in the Future (November 2022), 12, https://combicool.fi/media/2a/36/b3/1728580489/brochure-refrigerant-options-now-and-in-the-future-en-ast-ad224586434178en-001001.pdf; Scott Spielman, Seth McKinney, and Mark Frankel, Roadmap for Overcoming Barriers to Using Natural Refrigerants in the United States (Bonneville Power Administration, January 2024), https://www.bpa.gov/-/media/Aep/energy-efficiency/emerging-technologies/202401_e3t_natural_refrigerant_policy_whitepaper_final.pdf; Thomas Trevisan, Overview of PFAS Refrigerants Used in HVAC&R and Relevance of Refrigerants in the PFAS Restriction Intention (ATMO Network, July 2023), 4, https://ozone.unep.org/system/files/documents/OEWG45_ATMO_sidevent.pdf.

8 "Circular Economy Principles," Ellen MacArthur Foundation, https://www.ellenmacarthurfoundation.org/circular-economy-principles.

9 "Why FMHero," FMHero, https://www.fmhero.com/why-fmhero/; "A-Gas," A-Gas, https://www.agas.com/uk/.

10 Araceli Fernández et al., Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach (IEA, 2023), https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.

11 Ibid.

12 "Heat Pump Efficiency," Carrier, https://www.carrier.com/residential/en/us/products/heat-pumps/heat-pump-efficiency/.

13 David Roberts and Kathy Hannun, "Trying to Bring Geothermal Heat Pumps to the Masses," Volts (2023), https://www.volts.wtf/p/trying-to-bring-geothermal-heat-pumps; California Energy Commission, "Top Global Building Appliance Manufacturers and Distributors Commit to Help Meet Climate Goals," Press Release, October 2023, https://www.energy.ca.gov/news/2023-10/top-global-building-appliance-manufacturers-and-distributors-commit-help.

14 For examples see: Perrine Toledano, Sophie Thomashausen, Nicolas Maennling, and Alpa Shah, A Framework to Approach Shared Use of Mining-Related Infrastructure (New York: CCSI, 2014), https://ccsi.columbia.edu/sites/ccsi.columbia.edu/files/content/docs/publications/A-Framework-for-Shared-use_March-2014.pdf; Perrine Toledano, Leveraging the Mining Industry's Energy Demand to Improve Host Countries' Power Infrastructure (New York: CCSI, 2012), https://ccsi.columbia.edu/sites/ccsi.columbia.edu/files/content/docs/our%20focus/CCSI-Policy-Paper-Leveraging-mining-industry%E2%80%99s-energy-demand-to-improve-host-country%E2%80%99s-power-infrastructure-Sept-2012.pdf.

15 Park, Laying the Groundwork: Accelerating the HFCs Transition and Lifecycle Refrigerant Management – An HVACR Industry Survey, 11.

16 Hoover, Kilgore, and Torok, Refrigerants, Taking the Chill Out of Heat Pumps, 4.

17 Park, Laying the Groundwork: Accelerating the HFCs Transition and Lifecycle Refrigerant Management – An HVACR Industry Survey, 11.

18 Rhys Watt, Rosanna Jackson, Sabrina Kleissl, Paul Huggins, and Carbon Trust, Cooling Suppliers: A Stocktake on the Path to Net Zero (Carbon Trust and Cool Coalition, December 2023), https://ctprodstorageaccountp.blob.core.windows.net/prod-drupal-files/2023-12/Cooling%20supplier%20report.pdf.

19 Romain Poivet, Nicolas Pickard Garcia, Thomas Gourdo, and Adrien Rose, Assessing the Credibility of a Company's Transition Plan: Framework and Guidance (World Benchmarking Alliance (WBA) and CCSI, September 2024), 10, https://assets.worldbenchmarkingalliance.org/app/uploads/2024/09/ATP-Col-guidance-and-framework-document.pdf.

20 "Explore the Distribution of Companies Across All Sectors Based on Greenhouse Gas Emissions Management and Low-Carbon Transition Risks and Opportunities," Transition Pathway Initiative (TPI), TPI Global Climate Transition Centre at the London School of Economics and Political Science, https://www.transitionpathwayinitiative.org/sectors.

21 John Lang, Camilla Hyslop, Diego Manya, Sybrig Smit, Peter Chalkley, John Bervin Galang, Frances Green, Thomas Hale, Frederic Hans, Nick Hay, Angel Hsu, Denise Hsu, Takeshi Kuramochi, Steve Smith, Helen Tatlow, Net Zero Tracker: Methodology (Energy and Climate Intelligence Unit, Data-Driven EnviroLab, NewClimate Institute, and Oxford Net Zero, 2025), https://zerotracker.net/methodology.

22 "LobbyMap Data," LobbyMap, https://lobbymap.org/.

23 "About Us," Carbon Disclosure Project (CDP), https://www.cdp.net/en/about. Note: Transparency alone is not enough to show commitment to decarbonization, so the CDP should be used only as one part of a larger picture of proper behavior regarding transition planning and policy engagement.

24 International Energy Agency, The Future of Heat Pumps (Paris: IEA, 2022), 13, https://iea.blob.core.windows.net/assets/4713780d-c0ae-4686-8c9b-29e782452695/TheFutureofHeatPumps.pdf.

25 Chiara Delmastro, Robert Dubrow, Timur Gül, Araceli Fernandez Pales, Stéphanie Bouckaert, Rafael Martinez Gordon, and François Briens, Sustainable, Affordable Cooling Can Save Tens of Thousands of Lives Each Year (IEA, 2023), 1, https://www.iea.org/reports/sustainable-affordable-cooling-can-save-tens-of-thousands-of-lives-each-year.

26 World Energy Outlook (WEO), Sustainability, Technology and Outlooks (STO), and International Energy Agency (IEA), World Energy Outlook 2022 (IEA, 2022), 22, https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf.

27 M. González-Torres, L. Pérez-Lombard, Juan F. Coronel, Ismael R. Maestre, and Da Yan, "A Review on Buildings Energy Information: Trends, End-uses, Fuels and Drivers, Energy Reports, Vol. 8 (2021), 630, https://www.sciencedirect.com/science/article/pii/S235248472101427X.

28 "About F-Gases," Energy, Climate Change, Environment, European Commission, 2025, https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/about-f-gases_en.

29 "Hydrofluorocarbons and the Kigali Amendment to the Montreal Protocol," Harvard Law School Environmental and Energy Law Program, EPA, 2024, https://eelp.law.harvard.edu/tracker/hydrofluorocarbons-and-kigali-amendment-to-montreal-protocol/.

30 Nikolaos Barmparitsas, Sotirios Karellas, Platon Pallis, Sotirios Thanopoulos, and Daniel Kobelt, "An Innovative Heating, Ventilation, Air Conditioning and Refrigeration Circular Economy System for Reducing Carbon Dioxide Emissions in Europe via Extensive Reuse of Existing Fluorinated Gases," Energies, 16(23):7705, 2023, https://doi.org/10.3390/en16237705.

31 Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer, Art. 2(f).

32 IEA, The Future of Heat Pumps (2022).

33 Michael Gartman, Russell Unger, Rachel Golden, Jingyi Tang, and Ryan Shea, "What a 20 Million Heat Pump Commitment Means for the US," RMI, 2023, https://rmi.org/what-a-20-million-heat-pump-commitment-means-for-the-us/.

34 Institute For Governance & Sustainable Development, "China Issues Action Plan to Promote Development of the Heat Pump Industry," news brief, April 2, 2025, https://www.igsd.org/china-issues-action-plan-to-promote-development-of-the-heat-pump-industry/.

35 Fernández et al., Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach.

36 Hanlong Wan, Tao Cao, Yunho Hwang, Reinhard Radermacher, Stephen Oliver Andersen, and Simon Chin, "A Comprehensive Review of Life Cycle Climate Performance (LCCP) for Air Conditioning Systems," International Journal of Refrigeration, Vol. 130 (October 2021): 187–198, https://www.sciencedirect.com/science/article/pii/S0140700721002632.

37 Gang Li, " Comprehensive Investigations of Life Cycle Climate Performance of Packaged Air Source Heat Pumps for Residential Application," Renewable and Sustainable Energy Reviews, Vol. 43 (2015), https://www.sciencedirect.com/science/article/pii/S136403211401017X?via%3Dihub. Note: Around 80% of HVAC emissions come from energy consumption, ~10% come from leaked refrigerants, and ~1% come from material embodied emissions.

38 Wan et al. "A Comprehensive Review of LCCP," 189.

39 Adapted from: Wan et al. "A Comprehensive Review of LCCP," 190.

40 Hoover, Kilgore, and Torok, Refrigerants, Taking the Chill Out of Heat Pumps.

41 Park, Shah, and Gerke, Assessment of Commercially Available Energy-Efficient Room Air Conditioners Including Models With Low Global Warming Potential (GWP) Refrigerants, 4; Bolaji, "Theoretical Assessment of New Low Global Warming Potential Refrigerant Mixtures as Eco-Friendly Alternatives in Domestic Refrigeration Systems."

42 United Nations, Montreal Protocol on Substances that Deplete the Ozone Layer, 1522 U.N.T.S. (September 16, 1987), https://ozone.unep.org/treaties/montreal-protocol/montreal-protocol-substances-deplete-ozone-layer.

43 Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer, Art. 2(f).

44 "Kigali Amendment," Fluorocarbons, The European FluoroCarbons Technical Committee, https://www.fluorocarbons.org/regulation/global-regulation/kigali/.

45 Fabio Polonara, Lambert J.M. Kuijpers, and Roberto A. Peixoto, "Potential Impacts of the Montreal Protocol Kigali Amendment to the Choice of Refrigerant Alternatives," International Journal of Heat and Technology, Vol. 35, (2017), 3, https://www.iieta.org/sites/default/files/Journals/IJHT/35.Sp01_01.pdf.

46 "PFAS Ban Affects Most Refrigerant Blends," Cooling Post, February 2023, https://www.coolingpost.com/world-news/pfas-ban-affects-most-refrigerant-blends/.

47 "ECHA Publishes Updated PFAS Restriction Proposal," European Chemicals Agency, August 2025, https://echa.europa.eu/-/echa-publishes-updated-pfas-restriction-proposal. Note: "Conditional continued use" vaguely allows use of PFAS "where the risks can be controlled." The regulation is expected to be finalized by the end of 2026.

48 Park, Shah, and Gerke, Assessment of Commercially Available Energy-Efficient Room Air Conditioners Including Models With Low Global Warming Potential (GWP) Refrigerants, 4.

49 Organisation for Economic Co-operation and Development (OECD), Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Series on Risk Management No. 61 (July 2021), 32, https://www.oecd.org/en/publications/reconciling-terminology-of-the-universe-of-per-and-polyfluoroalkyl-substances_e458e796-en.html.

50 "Understanding PFAS: A Comprehensive Guide," United Diagnostic Services (UDS Health), January 2025, https://udshealth.com/blog/comprehensive-guide-to-pfas-per-and-polyfluoroalkyl-substances/.

51 Thomas Trevisan, Overview of PFAS Refrigerants Used in HVAC&R and Relevance of Refrigerants in the PFAS Restriction Intention, 4.

52 Michael Gerry, The Rising Threat of HFOs and TFA to Health and the Environment (ATMOsphere and Marc Chasserot, September 2022), 13, https://atmosphere.cool/hfo-tfa-report/.

53 Hans Peter H. Arp, Andrea Gredelj, Juliane Glügem, Martin Scheringerlan, and Ian T. Cousins, "The Global Threat from the Irreversible Accumulation of Trifluoroacetic Acid (TFA)," Environmental Science & Technology, Vol 58, Issue 45 (October 2024): 19925–19935, 19925, https://pubs.acs.org/doi/10.1021/acs.est.4c06189.

54 Ibid., 19928.

55 Ibid., 19930.

56 OECD, Synthesis Paper on Per and Polyfluorinated Chemicals (PFCs) (OECD/UNEP Global PFC Group, February 2013), 25, https://www.oecd.org/en/publications/synthesis-paper-on-per-and-polyfluorinated-chemicals_0bc75123-en.html.

57 European Union, Regulation (EC) No. 850/2004 On Persistent Organic Pollutants and Amending Directive 79/117/EEC, Regulation (EC) No. 850/2004, Doc. 32004R0850, Official Journal of the European Communities, L 158/7 (April 30, 2004) https://eur-lex.europa.eu/eli/reg/2004/850/oj/eng.

58 European Union, Commission Regulation (EU) No. 757/2010 of 24 August 2010 amending Regulation (EC) No. 850/2004 of the European Parliament and of the Council on Persistent Organic Pollutants as Regards Annexes I and III Text with EEA Relevance, Regulation (EU) No. 757/2010, Doc. 32010R0757, Official Journal of the European Union, L 223/29 (August 24, 2010), https://eur-lex.europa.eu/eli/reg/2010/757/oj/eng.

59 European Union, Regulation (EU) 2019/1021 of the European Parliament and of the Council of 20 June 2019 on Persistent Organic Pollutants, Regulation (EU) 2019/102, Doc. 32019R1021, Official Journal of the European Union, L 169/45 (June 20, 2019), https://eur-lex.europa.eu/eli/reg/2019/1021/oj/eng.

60 European Union, Commission Delegated Regulation (EU) 2023/1608 of 30 May 2023 Amending Annex I to Regulation (EU) 2019/1021 on Persistent Organic Pollutants as Regards the Listing of Perfluorohexane Sulfonic Acid (PFHxS), Its Salts, and PFHxS-Related Compounds, EU Doc. L198/24 (May 30, 2023) (Amendment of Annex I to Regulation (EU) 2019/1021), https://eur-lex.europa.eu/eli/reg_del/2023/1608/oj.

61 European Chemicals Agency, "Five European States Call for Evidence on Broad PFAS Restriction," news release, May 11, 2020, https://echa.europa.eu/-/five-european-states-call-for-evidence-on-broad-pfas-restriction.

62 European Chemicals Agency, To the Opinion on the Annex XV Dossier Proposing Restrictions on Per- and Polyfluoroalkyl Substances (PFASs): Background Document (Helsinki, June 24, 2025), https://echa.europa.eu/documents/10162/17233/rest_pfas_bd_draft_240625_en.pdf/86488ab5-30c9-f7b9-547d-84db15535d9a?t=1755590462498.

63 Trevisan, Overview of PFAS Refrigerants, 4.

64 Abas et al., "Natural and Synthetic Refrigerants." For example, ammonia is the refrigerant of choice for industrial refrigeration.

65 Abas et al., "Natural and Synthetic Refrigerants," 559; David A. Didion and Steven J. Brown, "Challenges in Developing Environmentally Safe Heat Pumping Systems," Proceedings of the International Thermal Science Seminar, Vol. 1 (2000): 57-66, 59, https://www.dl.begellhouse.com/references/1bb331655c289a0a,3d5d2dee7d4c7734,58693558409c9770.html.

66 Spielman et al., Roadmap for Overcoming Barriers to Using Natural Refrigerants in the United States.

67 "Have We Reached the Tipping Point for CO2 Refrigeration Systems?" Henderson Engineers, June 22, 2020, https://www.hendersonengineers.com/insight_article/have-we-reached-the-tipping-point-for-co2-refrigeration-systems/.

68 Tania Herreram, "Navigating the Transition to Natural Refrigerants: Contractors Can Help Customers Future-Proof Their Refrigeration Systems with CO_2 and Ammonia," The Air Conditioning, Heating, and Refrigeration News, August 6, 2025, https://www.achrnews.com/articles/165027-navigating-the-transition-to-natural-refrigerants.

69 "F-gas Legislation: Guidance on the EU's F-gas Regulation and its Legal Framework," Energy, Climate change, Environment, European Commission, https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/f-gas-legislation_en.

70 "PFAS Ban Affects Most Refrigerant Blends," Cooling Post.

71 "PFAS ban must overcome legal obstacles," Cooling Post, May 2025, https://www.coolingpost.com/features/pfas-ban-must-overcome-legal-obstacles.

72 Joanna R. Turpin, "EPA Issues Final Rule on HFC Phasedown: A Proposed Rule on Managing and Reusing Existing HFCs was also Published," The Air Conditioning, Heating, and Refrigeration News, October 8, 2023, https://www.achrnews.com/articles/153670-epa-issues-final-rule-on-hfc-phasedown.

73 "Protecting Our Climate by Reducing Use of HFCs," U.S. Environmental Protection Agency (US EPA), 2205, https://www.epa.gov/climate-hfcs-reduction.

74 Environmental Protection Agency (EPA), Phasedown of Hydrofluorocarbons: Restrictions on the Use of Certain Hydrofluorocarbons under the American Innovation and Manufacturing Act of 2020 (pre-publiction) (Environmental Protection Agency, October 2023), https://www.epa.gov/system/files/documents/2023-10/technology-transitions-final-rule-2023-pre-publication.pdf.

75 "PFAS Strategic Roadmap: EPA's Commitments to Action 2021-2024," PFOA, PFOS and Other PFAS, Environmental Protection Agency (EPA), June 11, 2025. https://www.epa.gov/pfas/pfas-strategic-roadmap-epas-commitments-action-2021-2024.

76 The ATMOsphere Podcast Network, Natural Refrigerants: State of the Industry 2024: U.S. EPA Excludes F-Gases and TFA from PFAS Definition (ATMOsphere, May 5, 2025), Chapter 3.2, https://atmosphere.cool/chapters_report/3-2-u-s-epa-excludes-f-gases-and-tfa-from-pfas-definition.

77 Institute for Governance & Sustainable Development, "China Issues National Plan to Strengthen the Management of Ozone-Depleting Substances and Climate-Polluting Hydrofluorocarbons," news brief, April 9, 2025, https://www.igsd.org/china-issues-national-plan-to-strengthen-the-management-of-ozone-depleting-substances-and-climate-polluting-hydrofluorocarbons/; The State Council of The People's Republic of China, "China Steps up Management of Ozone-Depleting Substances, HFCs to Tackle Climate Change," news release, April 23, 2025, https://english.www.gov.cn/news/202504/23/content_WS6808dfc4c6d0868f4e8f2021.html.

78 Institute for Governance & Sustainable Development, "China Issues Amended Regulation to Strengthen Its HFC Phasedown," news brief, January 4, 2024, https://www.igsd.org/china-issues-amended-regulation-to-strengthen-its-hfc-phasedown/.

79 Ministry of Ecology and Environment, People's Republic of China, Letter on Soliciting Public Comments for Three Indicative Lists Including the 'Indicative List of Long-Chain Perfluorocarboxylic Acids (PFCAs), Their Salts, and Related Compounds (Februrary 25, 2025), https://www.chemradar.com/lawinfo/news/detail/eezvvg1ips00.

80 Government of India, "Ministry of Environment, Forest and Climate Change Celebrates 29th World Ozone Day: Montreal Protocol: Fixing the Ozone Layer and Reducing Climate Change," press release, September 16, 2023, https://www.pib.gov.in/PressReleseDetail.aspx?PRID=1957968.

81 The Government of India Ministry of Environment, Forest, and Climate Change, India Cooling Action Plan: Operationalizing Transport Air Conditioning Sector Recommendations (New Dehli: September 2024), https://ozonecell.nic.in/wp-content/uploads/2024/09/2-Action-Plan-for-implementation-of-recommendations-of-ICAP-%E2%80%93-Transport-Air-Conditioning-Sector.pdf.

82 Government of India, "Ministry of Environment, Forest and Climate Change celebrates 29th World Ozone Day."

83 "Technology Transitions GWP Reference Table," U.S. EPA; Danfoss, Refrigerant Options Now and in the Future, 12; Spielman et al., Roadmap for Overcoming Barriers to Using Natural Refrigerants in the United States, 6; Thomas Trevisan, Overview of PFAS Refrigerants Used in HVAC&R and Relevance of Refrigerants in the PFAS Restriction Intention, 4.

84 Lindsay Rasmussen and Yulin Lou, "Clean Energy 101: Solid-State Cooling," RMI, March 13, 2025, https://rmi.org/clean-energy-101-solid-state-cooling.

85 Ibid.

86 Phononic, "Phononic Raises $50 Million Growth Financing from Goldman Sachs Asset Management to Scale Global Adoption of Sustainable Solid State Cooling Solutions," news release, https://phononic.com/resources/phononic-raises-50-million-growth-financing-from-goldman-sachs-asset-management/.

87 Cooling Post, "Carrier Invests in Solid-State Heat Pump," news release, December 6, 2024, http://coolingpost.com/world-news/carrier-invests-in-solid-state-heat-pump/.

88 Refrigerant Emissions Elimination Forum Refrigerant, REEF at Climate Week NYC Presents "Refrigerant 0: Powering a Net-Zero Future," October 7, 2025, Event Video, 53:05, https://www.reefclimate.org/climate-week-nyc-2025; REEF Refrigerant Emissions Elimination Forum, "The New Cool: Alternative Cooling Technologies," Linkedin Post, October 8, 2025, https://www.linkedin.com/posts/refrigerant-emissions-elimination-forum_alternativecooling-innovation-sustainability-activity-7381794845209628672-fsHq/.

89 Craig Bettenhausen, "Pascal Cuts the Climate Impacts of Climate Control: Switching to Solid Materials Promises to Stem Refrigerant Leaks that are Warming the Planet," Chemical and Engineering News, November 8, 2024, https://cen.acs.org/business/specialty-chemicals/Pascal-is-cutting-the-climate-impacts-of-climate-control/102/i35.

90 Cooling Post, "Carrier Invests in Solid-State Heat Pump."

91 Hoover, Kilgore, and Torok, Refrigerants, Taking the Chill Out of Heat Pumps, 4.

92 "Circular Economy Principles," The Ellen MacArthur Foundation.

93 Yeobeom Yoon, Piljae Im, Jon Winkler, and Jeffrey Munk, "Impact of Refrigerant Undercharge Faults on Building Indoor Conditions and HVAC System Operation in Residential Buildings: A Simulation Study," Energy and Buildings, Vol. 321, https://www.sciencedirect.com/science/article/abs/pii/S0378778824007837?via%3Dihub.

94 Daikin, "Daikin Expands Patent Non-Assertion Pledge for Air Conditioners Using Low GWP Refrigerant HFC-32: Providing Free Access to 419 Patents Including the Ones for VRF Co-owned by European Subsidiary," press release, July 1, 2022, https://www.daikin.com/press/2022/20220701; Christine Gibson, "Daikin Innovates to Tackle Hidden HVAC Leaks and Environmental Impact," https://hvac-blog.acca.org/daikin-innovates-to-tackle-hidden-hvac-leaks-and-environmental-impact/;

95 “Homepage,” Trane, https://t.trane.com/Link.html.

96 “Phoenix Energy Technologies Partners with Hussmann Corporation to Launch Refrigeration IQ, Powered by Hussmann StoreConnect, Revolutionizing AI-Driven, Refrigerant Leak Detection for Grocery Stores,” Phoenix Energy Techonolgies, March 5, 2025, https://www.phoenixet.com/press-releases/phoenix-energy-technologies-partners-with-hussmann-corporation-to-launch-refrigeration-iq-powered-by-hussmann-storeconnect-revolutionizing-ai-driv-174112690426.

97 “HVAC Systems: How to Maximize the Longevity of Your Equipment,” Institute of Supply Chain Management, July 12, 2024, https://www.ioscm.com/blog/hvac-systems-how-to-maximise-the-longevity-of-your-equipment.

98 Refrigerant Emissions Elimination Forum Refrigerant, REEF at Climate Week NYC presents “Refrigerant 0: Powering a Net-Zero Future,” 53:05.

99 “Background on HFC Reclamation and Destruction,” U.S. Environmental Protection Agency, November 26, 2024, https://www.epa.gov/climate-hfcs-reduction/background-hfc-reclamation-and-destruction.

100 Aditya Garg, Sonal Kumar, Shikha Bhasin, and Torgrim Asphjell, Activating Circular Economy for Sustainable Cooling Global Best Practices on Lifecycle Refrigerant Management (May 2023), 1, https://www.ccacoalition.org/sites/default/files/resources/files/Global-Best-Practices-Lifecycle-Refrigerant-Management-Emissions.pdf.

101 Garg et. al, Activating Circular Economy for Sustainable Cooling Global Best Practices on Lifecycle Refrigerant Management, 2-7.

102 “Regulatory Actions for Managing HFC Use and Reuse,” U.S. Environmental Protection Agency, September 29, 2025, https://www.epa.gov/climate-hfcs-reduction/regulatory-actions-managing-hfc-use-and-reuse.

103 European Union, Regulation (EU) 2024/573 on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) No. 517/2014, 2024/5 (February 20, 2024), https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ%3AL_202400573.

104 Institute For Governance & Sustainable Development, “China Policy Developments Provide Opportunities to Tackle Lifecycle Refrigerant Management in the Cooling Equipment End-of-Life Recycling and Disposal Processes,” news brief, July 24, 2025, https://www.igsd.org/china-policy-developments-provide-opportunities-to-tackle-lifecycle-refrigerant-management-in-the-cooling-equipment-end-of-life-recycling-and-disposal-processes.

105 “The Air-Conditioning, Heating, and Refrigeration Institute,” AHRI, https://www.ahrinet.org/.

106 “AHRI 700 (SI): Specifications for Refrigerants,” AHRI, https://www.ahrinet.org/search-standards/ahri-700-si-specifications-refrigerants.

107 “Reclaimed Refrigerant (RECL),” AHRI, https://www.ahrinet.org/certification/ahri-certification-programs/reclaimed-refrigerant-recl

108 Trane Technologies, Accelerating Action for Impact: 2023 ESG Report (2023), 80, https://www.tranetechnologies.com/content/dam/cs-corporate/pdf/sustainability/annual/2023-ESG-Report.pdf.

109 “L∞p by Daikin,” Daikin Global, https://www.daikin-ce.com/en_us/about/environmental-responsibility/loop-by-daikin.html.

110 “Building a Sustainable Future,” A-Gas International Ltd, https://www.agas.com/uk/.

111 “Daikin to Offer Air Conditioners in Africa on Daily Rental,” CoolPost, June 7, 2020, https://www.coolingpost.com/world-news/daikin-to-offer-air-conditioners-in-africa-on-daily-rental/#:~:text=7th%20June%202020,even%20in%20small%20immature%20markets; “Baridi Baridi Launches CaaS Subscription Offering Air-Conditioning as a Service,” SET Alliance, January 4, 2021, https://www.caas-initiative.org/news/baridi-baridi-launches-caas-subscription-offering-air-conditioning-as-a-service/.

112 “Homepage,” Baridi Baridi,https://baridibaridi.co.tz/about.

113 Hoover, Kilgore, and Torok, Refrigerants, Taking the Chill Out of Heat Pumps, 10.

114 Ankit Kalanki, Yulin Lou, Ian McGavisk, Raghav Muralidharan, Hadia Sheerazi, and Gareth Westler, Assessing Potential Emissions Impact of R-410A Refrigerant Reclamation in the United States’ Residential HVAC Sector (Refrigerant Reclamation, September 2024), https://www.hudsontech.com/pdfs/RMI-Buildings-Refrigerant-Reclamation-Report.pdf.

115 “The A2L Refrigerant Transition: A Guide For HVAC Distributors,” GE Appliances, December 12, 2024, https://www.geappliancesairandwater.com/the-a2l-refrigerant-transition-a-guide-for-hvac-distributors.

116 “2025 Low GWP Compliant Refrigerants: Why Lennox is your Perfect Partner for the 2025 Refrigerant Transition,” LennoxPros, https://www.lennoxpros.com/news/transitioning-to-low-gwp-refrigerants.

117 “Why FMHero?” FMHero, https://www.fmhero.com/why-fmhero/.

118 Refrigerant Emissions Elimination Forum Refrigerant, “Powering a Net-Zero Future,” 43:00.

119 Kalanki et al., Assessing Potential Emissions Impact of R-410A Refrigerant Reclamation in the United States’ Residential HVAC Sector, 29.

120 More information here: Energy Efficient End-use Equipment TCP, PEET Efficiency Trends Analysis: Status of Room Air Conditioner Regulations (July 2022), https://www.iea-4e.org/peet/publications/4e-peet-status-of-room-air-conditioner-regulations-2022/.

121 “Details to Understanding How Efficient Your Air Conditioner Is,” Atlantis Solar, https://www.atlantissolar.com/cop_eer.html.

122 Won Young Park, Nihar Shah, Jun Young Choi, Hee Jeong Kang, Dae Hoon Kim, and Amol Phadke, “Lost in Translation: Overcoming Divergent Seasonal Performance Metrics to Strengthen Air Conditioner Energy-Efficiency Policies,” Energy for Sustainable Development, Vol. 55, (April 2020): 56-68, 57, https://www.sciencedirect.com/science/article/pii/S0973082619313560.

123 “Efficiency Ratings of Available AC Units by Regional Metric,” International Energy Agency, June 3, 2020, https://www.iea.org/data-and-statistics/charts/efficiency-ratings-of-available-ac-units-by-regional-metric.

124 "ENERGY STAR Most Efficient 2025," Energy Star, https://www.energystar.gov/products/most_efficient.

125 "ENERGY STAR Most Efficient Air-Source Heat Pumps," Energy Star, October 16, 2025, https://data.energystar.gov/Active-Specifications-Most-Efficient/ENERGY-STAR-Most-Efficient-Air-Source-Heat-Pumps/.

126 "CEE Tiers and ENERGY STAR," Consortium for Energy Efficiency, https://cee1.org/program-resources/tiers-and-energy-star/.

127 "Standards & Labelling," BEE India, Bureau of Energy Efficiency, March 6, 2025, https://beeindia.gov.in/en/star-label.

128 "Search and Compare," BEE India, Bureau of Energy Efficiency, https://www.beestarlabel.com/SearchCompare.

129 "China Energy Efficiency Label Certification," NTEK, https://www.ntek.org.cn/en/200/104-338.html.

130 "Front Page," China Energy Efficiency Labeling Network, China National Development and Reform Commission, https://www.energylabel.com.cn/indexEnergy; "China: Compulsory Energy Efficiency Label," Solar Thermal World, January 17, 2013, https://solarthermalworld.org/news/china-compulsory-energy-efficiency-label/.

131 "Energy Labels," Your Europe, European Union, https://europa.eu/youreurope/citizens/consumers/shopping/energy-labels/index_en.htm.

132 "EPREL - European Product Registry for Energy Labelling," European Union, September 9, 2024, http://eprel.ec.europa.eu/screen/product/airconditioners.

133 Ankita Singh Gaur, Desta Z. Fitiwi, and John Curtis, "Heat Pumps and Our Low-Carbon Future: A Comprehensive Review," Energy Research & Social Science, Vol. 71 (January 2021), https://www-sciencedirect-com.ezproxy.cul.columbia.edu/science/article/pii/S221462962030339X.

134 Doug Davis, "How Heat Pumps Achieve Their Amazing Efficiency," A/C & Plumbing Doctors, https://theacdoctors.com/how-heat-pumps-achieve-their-amazing-efficiency/. Heat pump efficiency is measured in Coefficient of Performance (COP), while furnaces are measured in Annual Fuel Utilization Efficiency (AFUE). Despite differing names, the two are directly comparable: a COP of 4.0 is an AFUE of 400%, meaning 4 units of heat for every 1 unit of power used. A COP of 4 is average for a heat pump, but furnaces literally cannot exceed a COP of 1 (or AFUE of 100%).

135 Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach (IEA, 2023).

136 "Schematic: Heat Pump Types and Applications," IEA, https://www.iea.org/reports/the-future-of-heat-pumps-in-china/schematic-heat-pump-types-and-applications.

137 "Ductless Heating & Cooling," Energy Star, https://www.energystar.gov/products/ductless_heating_cooling.

138 "What's an Inverter? An Inverter Is Energy-Saving Technology That Eliminates Wasted Operation in Air Conditioners by Efficiently Controlling Motor Speed," Daikin, https://www.daikin.com/air/daikin_techknowledge/benefits/inverter.

139 "The Importance of HVAC Zoning in Multi-Tenant Buildings," Cadence, https://cadencenow.com/the-importance-of-hvac-zoning-in-multi-tenant-buildings/.

140 "Overview of Key Barriers to Accelerating the Deployment of Heat Pumps and Corresponding Policy Solutions," IEA, https://www.iea.org/reports/the-future-of-heat-pumps/overview-of-key-barriers-to-accelerating-the-deployment-of-heat-pumps-and-corresponding-policy-solutions.

141 Urban Green Council, Going Electric: Retrofitting NYC's Multifamily Buildings (New York: April 2020), https://www.urbangreencouncil.org/wp-content/uploads/2022/11/2020.04.22-Going-Electric-v2.pdf.

142 Ibid.

143 Agne Toleikyte, Juan Carlos Roca Reina, Jonathan Volt, Johan Carlsson, Lorcan Lyons, Andrea Gasparella, Derck Koolen, Matteo De Felice, Dalius Tarvydas, Veronika Czako, Giorgos Koukoufikis, Anna Kuokkanen, and Simon Letout, The Heat Pump Wave: Opportunities and Challenges — Analysis of the Large-Scale Deployment of Heat Pumps by 2030 Following the REPowerEU Plan (Luxembourg: European Union, 2023), https://build-up.ec.europa.eu/system/files/2023-07/JRC134045_01.pdf.

144 For examples see: Perrine Toledano, Sophie Thomashausen, Nicolas Maennling, and Alpa Shah, A Framework to Approach Shared Use of Mining-Related Infrastructure (New York: CCSI, 2014), https://ccsi.columbia.edu/sites/ccsi.columbia.edu/files/content/docs/publications/A-Framework-for-Shared-use_March-2014.pdf; Perrine Toledano, Leveraging the Mining Industry's Energy Demand to Improve Host Countries' Power Infrastructure (New York: CCSI, 2012), https://ccsi.columbia.edu/sites/ccsi.columbia.edu/files/content/docs/our%20focus/CCSI-Policy-Paper-Leveraging-mining-industry%E2%80%99s-energy-demand-to-improve-host-country%E2%80%99s-power-infrastructure-Sept-2012.pdf.

145 International Energy Agency, The Future of Heat Pumps.

146 Trane Technologies, "Trane Technologies Advances Transformational Heat Pump Technologies to Decarbonize America's Industrial Sector," news release, June 26, 2023, https://investors.tranetechnologies.com/news-and-events/news-releases/news-release-details/2023/Trane-Technologies-Advances-Transformational-Heat-Pump-Technologies-to-Decarbonize-Americas-Industrial-Sector/default.aspx.

147 Hoval, "Hoval Invests in Heat Pump Production," press release, 2022, https://www.hoval.com/en/Hoval-invests-in-heat-pump-production/news/news-waermepumpenproduktion.

148 Viessman Climate Solutions, "Viessmann Group to Invest EUR 1 Billion in Heat Pumps & Green Solutions," press release, May 2, 2022, https://www.viessmann-climatesolutions.com/en/newsroom/company/viessmann-group-to-invest-eur-1-billion-in-heat-pumps-and-green-solutions.html.

149 California Energy Commission, "Top Global Building Appliance Manufacturers and Distributors Commit to Help California Achieve Six Million Heat Pump Goal," news release, October 10, 2023, https://www.energy.ca.gov/news/2023-10/top-global-building-appliance-manufacturers-and-distributors-commit-help.

150 David Robert and Kathy Hunnan, “Trying to Bring Geothermal Heat Pumps to Scale,” https://www.volts.wtf/p/trying-to-bring-geothermal-heat-pumps?utm_source=substack&publication_id=193024&post_id=161440563&utm_medium=email&utm_content=share&utm_campaign=email-share&triggerShare=true&isFreemail=true&r=58cj2e&triedRedirect=true.

151 International Energy Agency, The Future of Heat Pumps.

152 Michael Taylor, Meysam Qadrdan, Bridget Woodman, and Jianzhong Wu, “The Future of District Heating and Cooling Networks,” (UK Energy Research Centre Working Paper, May 2023), https://ukerc.rl.ac.uk/publications/working_paper/UKERC_The-Future-of-District-Heating-and-Cooling-Networks.pdf.

153 Juliet G. Simpson, Nicholas Long, and Guangdong Zhu, “Decarbonized District Energy Systems: Past Review and Future Projections”, Energy Conversion and Management: X, Vol. 24 (October 2024), https://docs.nrel.gov/docs/fy25osti/89809.pdf.

154 Carbon Trust, Cool Coalition, High-Level Champions, Kigali Cooling Efficiency Program, and Oxford Martin School at the University of Oxford, Climate Action Pathway: Net-Zero Cooling (March 2021), https://www.carbontrust.com/our-work-and-impact/guides-reports-and-tools/the-climate-action-pathway-for-net-zero-cooling.

155 For additional design, climate, and operational considerations on passive and radiant strategies, see International Energy Agency, “Staying cool without overheating the energy system”, https://www.iea.org/commentaries/staying-cool-without-overheating-the-energy-system

156 Park, Laying the Groundwork: Accelerating the HFCs Transition and Lifecycle Refrigerant Management – An HVACR Industry Survey, 11.

157 Watt et al., Cooling Suppliers: A Stocktake on the Path to Net Zero.

158 Poivet et al., Assessing the Credibility of a Company’s Transition Plan: Framework and Guidance, 10.

159 “Exploring the Distribution of Companies Across All Sectors Based on Greenhouse Gas Emissions Management and Low-Carbon Transition Risks and Opportunities,” Transition Pathway Initiative,

160 “Methodology,” Net Zero Tracker” Energy and Climate Intelligence Unit, Data-Driven EnviroLab, NewClimate Institute, and Oxford Net Zero, 2025, https://zerotracker.net/methodology.

161 “About Us,” CDP, CDP Worldwide, https://www.cdp.net/en/about. Transparency alone is not enough to show commitment to decarbonization, so the CDP should be used only as one part of a larger picture of proper behavior regarding transition planning and policy engagement

162 “LobbyMap,” InfluenceMap, https://lobbymap.org/.

163 “Corporate Policy Engagement Disclosure Scorecards,” InfluenceMap, https://ca100.influencemap.org/lobbying-disclosures.

164 International Energy Agency, The Future of Heat Pumps, 13

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Sustainability Best Practices
in the HVAC Industry

Stewart Investors

Columbia Climate School
Columbia Center on
Sustainable
Investment