Consistent Refrigerant Policy Is Essential for Investment in Industrial Heat Pump Market Transformation

JANUARY 2024

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Key takeaways

- Refrigerants are critical to the performance of industrial heat pumps (IHPs), but uncertainty regarding the future availability and regulation of refrigerants makes manufacturers reluctant to enter the market.
- Consistent and stable policies surrounding refrigerants are essential for IHP manufacturers to plan and design their products, especially in a fledgling market.
- Policymakers and regulators, especially those at the Environmental Protection Agency (EPA), should be careful not to overregulate refrigerants without extensive additional research into their environmental effects and efficacies.
- Industrial end users interested in IHPs will need to understand the role of refrigerants and the relevant state or regional regulations to decide on IHP system design for their applications, further underscoring the need for consistent refrigerant policies.
- The refrigerant landscape is diverse and constantly shifting. This brief introduces available products and helps define their emerging roles in the IHP space regarding temperatures delivered, pressures, and performance.

Industrial heat pumps can significantly reduce emissions.

Industrial heat pumps (IHPs) have the potential to cut industrial fossil fuel energy use by 1/3 and significantly reduce greenhouse gas emissions for many industries that have significant process heat demands, particularly at low-to-medium temperatures. Since only about 5% of on-site industrial energy produced and used for process heat is electrified, with the remainder supplied by the combustion of fossil fuels, decarbonization potential remains largely untapped. Review the resources on ACEEE's IHP web page for more information.

IHP manufacturers must have certainty that refrigerant choices will be available and acceptable to end users.

As the North American IHP market rapidly accelerates, one area needing more attention is refrigerants, the working fluids used in the refrigeration vapor compression cycles of heat pumps. IHP manufacturers report that inconsistent regulatory policy for refrigerants across the economy is limiting their ability to scale up production. Some inconsistency in policy stems from regulators' incomplete understanding of the best applications for different refrigerants.

Industrial heat pumps operate on basic refrigeration principles, using electric or steam-driven mechanical compression of working fluids or gases (refrigerants) to move heat. IHPs are designed and produced around the properties of a best-fit refrigerant, and several categories of refrigerants are used in heat pumps. Each has different ideal applications based on varying factors, including

- energy performance
- flammability
- toxicity
- global warming potential (GWP) [1]
- ozone depleting potential (ODP)
- other safety and environmental risks such as leaks, spillage, and improper disposal.

Given these diverse applications and risks, the United States currently has an inconsistent and confusing array of refrigerant policies that differ extensively by state. Bans on hydrofluorocarbons (HFCs), for example, vary significantly by state authority. Some states already have strict bans in place, while others are planning for phase out, and others still have no or little approved regulation. On the federal level, the Environmental Protection Agency (EPA) only recently passed a rule for nationwide phasedown of HFCs, which highlights the inconsistency between federal and state refrigerant regulations. For manufacturers to scale up investment, they need to have certainty that refrigerant choices will continue to be available for a reasonable period of time and be acceptable to targeted end users across the country. Therefore, the large-scale transformation of the IHP market requires a comprehensive review of refrigerant availability and suitability by federal and state authorities and clear and consistent policies regarding the future of refrigerants.

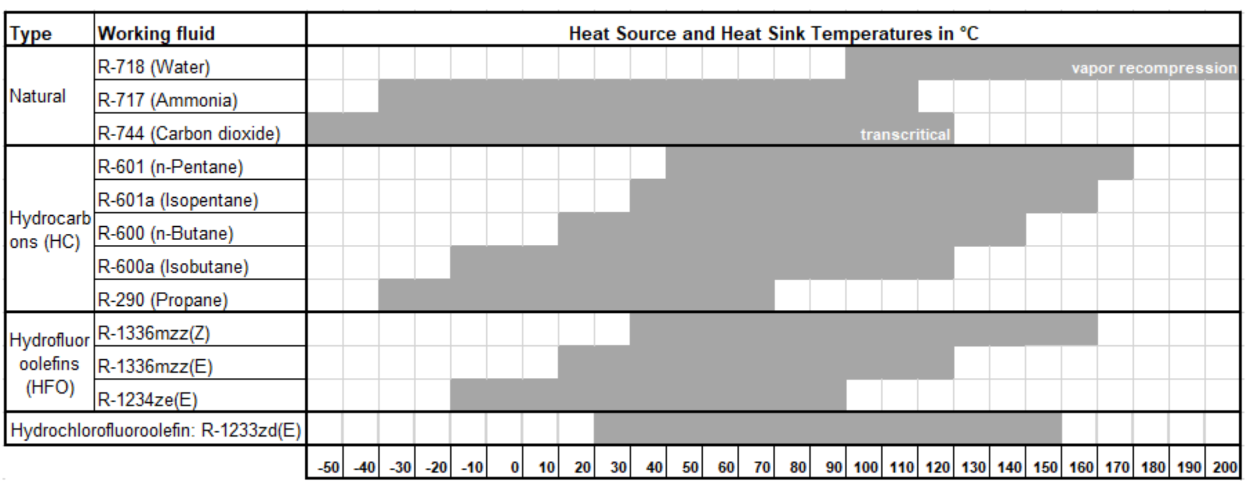

Figure 1. Temperature application ranges for refrigerants in IHPs. Source: Annex 58. [2]

[1] Note that while GWP is an important metric to capture, it is typical that refrigerants account for less than approximately 10% of the scope 3 emissions associated with IHPs.

[2] This figure's temperature ranges are theoretical. Typically, evaporators operate 20°C above the minimum boiling temperature (low temp, leftmost value) while condensers operate 30–40°C below the critical temperature (high temp, rightmost value)

Figure 1 depicts refrigerants by type, working fluid, and heat source/sink temperatures (adapted from the International Energy Agency's (IEA) Annex 58 Task 1). Using IHPs to decarbonize industrial process heat will require many heat pump products using a variety of refrigerants to reach the temperatures and pressures needed. Ammonia, for example, is a widely used, versatile refrigerant that can be compressed to high pressures and delivers relatively high heat at good coefficients of performance (COP)[3] and has no GWP. Additionally, some industrial facilities are already very familiar with ammonia and have the infrastructure in place for its use. Despite this, some jurisdictions, especially in the buildings sector, restrict the use of ammonia as a refrigerant because of its toxicity and light flammability, and some potential end users are uncomfortable with its use due to lack of experience. Meanwhile, hydrofluoroolefins/hydrochlorofluoroolefins (HFOs/HCFOs) are increasingly popular because of their high COP and ultra-low GWP. Still, there is regulatory uncertainty about their use due to concerns about potential breakdown into trifluoroacetic acid (TFA), a substance some have suggested is an environmental and health concern, though analyses by the U.S. EPA and United Nations Environment Programme (UNEP) conclude otherwise.[4]

Each refrigerant has properties that make it most suitable for specific industrial applications; effective pairing of refrigerants with applications will maximize impact.

Table 1 depicts the most important benefits and drawbacks of each refrigerant. Minimal GWP (0–5) and higher COP (indicating better system efficiency) values are desirable, while safety group A1 is ideal as it denotes both low toxicity and low flammability. Some trade-offs may be more acceptable to specific end users and manufacturers. Note that all listed refrigerants have an ODP of 0, except for R-1233zd(E), which has an ODP of 0.00034.

[3] COP refers to the ratio of process heat delivered to input energy required.

[4] https://ozone.unep.org/sites/default/files/2019-08/TFA2016.pdf

Table 1. Potential working fluids for IHP consideration

Refrigerant	GWP	COP [5]	Temperatures delivered[6,7]	Pressure (bar at critical temperature)[8]	ASHRAE safety group[9]	Potential end uses
Water (R-718)	0	N/A	100 to 200°C	16 (at 200°C)	A1	Food and beverage, drying, sewage, pulp and paper, refining, chemicals/plastics
Ammonia (R-717; NH3)	0	4.34	–40 to 95°C	56 (at 95°C)	B2L	Food and beverage, drying, pharmaceuticals
Carbon dioxide (R-744)[10]	1	N/A	–50 to 62°C	154 (at 62°C)	A1	Food and beverage
n-Pentane (R-601)	5–20	N/A	30 to 180°C	26 (at 180°C)	A3	Food and beverage
Isopentane (R-601a)	4–20	N/A	–3 to 180°C	30 (at 180°C)	A3	Food and beverage
n-Butane (R-600)	4–20	N/A	–20 to 147°C	35 (at 147°C)	A3	Food and beverage
Isobutane (R-600a)	3–20	4.37	–39 to 130°C	33 (at 130°C)	A3	Food and beverage
Propane (R-290)	3	3.78	–40 to 80°C	31 (at 80°C)	A3	Food and beverage
HFO: R-1336mzz(Z)	2	4.60	10 to 166°C	27 (at 166°C)	A1	Food and beverage, minerals, drying, sewage, pulp and paper, refining, chemicals/plastics
HFO: R-1336mzz(E)	18	4.31	4 to 166°C	27 (at 166°C)	A1	Food and beverage, minerals
HFO: R-1234ze(E)	≤1	4.09	–30 to 90°C	30 (at 90°C)	A2L	Chemical, pulp and paper, food and beverage
HCFO: R-1233zd(E)	1–4.5	4.65	–10 to 161°C	33 (at 161°C)	A1	Chemical, pulp and paper, food and beverage

[5] T Condenser = 40°C, T Evaporator = 90°C. Source: pers. comm. with Jethro Medina, Chemours. N/A indicates insufficient data.

[6] These temperature ranges are practical, whereas those in figure 1 are theoretical.

[7] These values were obtained from the Danfoss Ref Tools app found here: https://reftools.danfoss.com/spa/tools#/.

[8] Ibid.

[9] The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)'s safety groups classify refrigerants into groups based on toxicity and flammability. The letter (A and B) describes toxicity, where Class A is lower toxicity and Class B is higher toxicity. The number (1, 2, or 3) denotes flammability, increasing from 1 to 3. The group 2 subclass (2L) includes class 2 refrigerants that burn very slowly.

[10] CO_2 heat pumps are typically for small, domestic applications. If configured in a return loop, the return temperature must be lower than approximately 45°C, limiting industrial applications.

Natural refrigerants

Water is a natural refrigerant that can be used for temperatures above 150°C because of water's large latent heat. However, water vapor's low density and low volumetric capacity require several compression stages using large or high-speed compressors that can facilitate high flow rates and low-pressure ratios. This can reduce the overall operational efficiency of the system. Water is an attractive refrigerant for 0 GWP, is low cost, and is abundantly available.

Ammonia, a natural refrigerant with 0 GWP, has been used in many cooling applications and is well suited for IHP applications where heat sink temperatures reach up to 95°C. The high volumetric heating capacity (VHC) of ammonia results in high vaporization latent heat, but equipment has yet to be developed for using ammonia above 95°C. Safety concerns with the mild flammability and airborne and aquatic toxicity of ammonia must be addressed with leak technology and dedicated professional management. Refrigerants at higher pressures typically have more significant leakage concerns, and adequate safeguards must be used to prevent leakages. However, several well-established institutions in the United States, including the Refrigerating Engineers and Technicians Association and others, support training and education on ammonia use that will serve as essential resources for mitigating risks.

Carbon dioxide is a nontoxic, nonflammable natural refrigerant with an extremely low GWP value of 1. It is suitable for transcritical cycles (at higher costs) where the working fluid undergoes subcritical and supercritical[11] phases. Carbon dioxide as a refrigerant is more affordable to produce than HFCs and HFOs in some hot-water or hot air processes. CO_2 is already being used in small domestic heat pumps. There is potential for repurposing captured carbon as a refrigerant, contributing to a more circular economy and reducing carbon emissions. However, this would add significant costs. The high working pressures of carbon dioxide make it ideal in free cooling applications[12] where ambient temperatures are favorable.

Hydrocarbons consist of n-butane, n-pentane, and propane. Hydrocarbons are used as refrigerants due to low GWP (≤20), but special safety precautions must be taken as they are highly flammable and explosive. The temperatures of these working fluids are already achievable in standard equipment today. Hydrocarbons are applicable for industrial and district heating applications where refrigerant charges can be higher when appropriate safety measures and equipment are in place. Hydrocarbons are a widely used refrigerant in the petrochemical industry.

Alternative synthetic refrigerants

Alternative synthetic refrigerants such as HFOs and HCFOs are gaining popularity as more research confirms their high VHC. The design trade-off for these synthetic fluids is between a high COP or high VHC, depending on the application.

Hydrofluoroolefins (HFOs) are a type of alternative synthetic working fluid with ultra-low GWP (most are <5). HFOs are attractive as replacements for HFCs (e.g., R-365mfc and R-245fa), a group of high GWP (800–1,300) synthetic refrigerants that are being phased out under regulatory programs in Europe, North America, and parts of Asia. HFOs have low to no flammability and no toxicity, and the highest GWP value for any type of HFO is 18. However, HFOs, like HFCs, are considered fluorinated greenhouse gases (F-gases), and manufacturing F-gases currently creates more CO_2e emissions than manufacturing

[11] Supercritical is the state in which the substance is neither fluid nor gas beyond the critical point (the critical point is when the liquid and vapor phase of the substance have the same density). Subcritical refers to when the state is still below the critical point. Transcritical cycles happen when the substance undergoes a cycle in both subcritical and supercritical regions.
[12] Free cooling is a method of using low ambient air temperatures to assist in cooling water.

other working fluids. There are some concerns about decomposition to TFA. HFOs are still being researched but could be especially suitable for heat recovery applications.

Hydrochlorofluoroolefins (HCFOs) are another type of alternative synthetic working fluid with very low GWP, close to zero ODP, and low to no flammability. These F-gases are used in waste heat recovery applications. R-1233zd(E) has been found to be a suitable replacement for HFC R-245fa, with an atmospheric lifetime associated with its small ODP of only about 21 days. However, like HFOs, R-1233zd(E) has a small TFA formation risk.

Note that the above list is non-exhaustive, especially considering that there are multiple types of refrigerant blends used in other applications, such as commercial refrigeration, that have a potential for use in IHPs. For example, ammonia and water mixtures are being sold up to 120°C.

Manufacturers require consistent and predictable refrigerant regulations to proceed with IHP development.

The refrigerant landscape is continually shifting because of the developing end-user demand market and regulatory considerations. In the European Union, for example, new provisional regulations (for heat pumps between 12 and 50 kW in capacity) require GWPs of F-gases to be less than 150, except when safety requires the use of another refrigerant or blend of refrigerant (in which case the maximum GWP is 750). There have been other recent proposals in the EU's parliament to further restrict HFOs because of their potential to leave behind TFAs. While no such ban or limitation on HFOs currently exists in the United States, there is some doubt about their long-term regulatory approval. This unpredictable regulatory environment makes it difficult for IHP manufacturers to plan product design and deployment tailored to the optimal working fluid for each application. To seize the full decarbonization opportunity afforded by the increasing feasibility of IHPs, policymakers must develop consistent, nationwide refrigerant policies and regulations. Policymakers should consider and evaluate statewide policies currently in effect. For the state and utility funding and programming timeline that ACEEE has projected to be possible (which includes pilots and incentive programs for IHPs by 2025), there needs to be adequate IHP supply. Thus, policymakers and government agencies like EPA should avoid creating regulatory uncertainty.

Next steps: Demonstrate the efficacy and safety of specific refrigerants for specific end uses.

Pilots and demonstrations at sites across the country need to use the full suite of refrigerants outlined above to demonstrate their efficacy and effectiveness in different applications. National research institutions can analyze refrigerants to determine the full scope of their environmental effects and to what extent the reductions in fossil fuel use enabled by IHPs may outweigh the GWP of their potential leakage.

Refrigerant choice will largely depend not only on regulation but also on the segmentation of the end-user market. Some end users are better positioned to safely use one refrigerant type over another and adequately manage any associated risks. Clear information on these distinctions is critical for IHP manufacturers deliberating which equipment sizes and end-user subsectors they should be targeting, as well as for end users deciding which IHP products are best suited for their requirements. ACEEE plans a forthcoming topic brief on this market segmentation approach to understanding refrigerant availability and associated workforce needs.

The IHP Alliance, composed of ACEEE and our partners, the National Electrical Manufacturers Association and the Renewable Thermal Collaborative, is working to ensure that confusion and risk aversion regarding refrigerants do not obstruct IHP market transformation. We plan to help develop future-facing, long-term policies on refrigerant regulation in communications with relevant stakeholders and government agencies.

Our team is engaging with companies from across the diverse supply chain, as well as federal, state, and utility-level agencies and offices, to ensure that the connective infrastructure and knowledge base is adequate to support the transition. DOE's Industrial Heat Shot, for example, is aiming to help develop industrial heat decarbonization technologies, including IHPs, with at least 85% lower greenhouse gas emissions by 2035, while several provisions of both the Inflation Reduction Act and the Bipartisan Infrastructure Law earmark emerging funds for IHP market stimulus and implementation.

Table 2. Next step action items, probable actors, and timeframe

Action	Actor	Timeframe
Research is needed to determine the full scope of environmental effects of refrigerants, and their net impact to emission reductions	National labs, Electrified Processes for Industry without Carbon Institute at Arizona State University, Technical Assistance Partnership hubs	2024–
Policy consistency is needed to enable refrigerant certainty and enable manufacturers to enter the market at scale. Additional research is needed to determine best practices and policies that can be gleaned from the EU experience, global perspective	IHP Alliance communication with relevant policymakers, stakeholders, and state and federal government agencies including EPA and DOE	2024–
Refrigerant choice and efficacy should be an early focus in IHP pilots and demonstrations that are urgently needed in larger market transformation efforts	IHP Alliance, utilities, end users, other supporting entities and institutions	2025–
Market segmentation approach to refrigerants is needed to inform end users which IHP products and associated working fluids may be best for their requirements	ACEEE, upcoming policy brief	Early 2024

Further reading (in order of reference):

ACEEE's IHP Web Page includes all our IHP work to date, including research reports, blog posts, articles, and presentations: www.aceee.org/industrial-heat-pumps

The International Energy Agency's High Temperature Heat Pump Annexes provide overviews of available IHP technologies, readiness levels, economics, and savings. The most recent version is the ongoing Annex 48, which includes data from 14 participating countries: heatpumpingtechnologies.org/annex58/

The Danfoss tool Ref Tools is a free app that allows users to calculate pressure-temperature ratios on more than 80 refrigerants: www.danfoss.com/en-us/service-and-support/downloads/dcs/ref-tools/#tab-overview

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)'s refrigerant designations and safety classifications are an essential tool for understanding refrigerant properties and applicability in terms of flammability, toxicity, and other metrics: www.ashrae.org/file%20library/technical%20resources/bookstore/factsheet_ashrae_english_november2022.pdf

A research paper, "High Temperature Heat Pump Using HFO and HCFO Refrigerants—System Design, Simulation, and First Experimental Results," written for the International Refrigeration and Air Conditioning Conference at Purdue in 2018, includes critical details on VHC of HFOs: www.researchgate.net/publication/326847793_High_Temperature_Heat_Pump_using_HFO_and_HCFO_refrigerants_-_System_design_simulation_and_first_experimental_results

The EU's agreement on fluorinated gases and ozone depleting substances: www.consilium.europa.eu/en/press/press-releases/2023/10/05/fluorinated-gases-and-ozone-depleting-substances-council-and-parliament-reach-agreement/

DOE's Industrial Heat Shot includes details on the plan to develop industrial heat decarbonization technologies with at least 85% lower greenhouse gas emissions by 2035: www.energy.gov/eere/industrial-heat-shot

Acknowledgments

This topic brief was made possible through the generous support of Breakthrough Energy and Energy Innovation. The authors gratefully acknowledge external reviewers, internal reviewers, colleagues, and sponsors who supported this brief. External expert reviewers included Patricia Provot, Raj Gnanaraj, and Rossen Ivanov from Armstrong International, German Robledo from GEA, Mark Lessans and Curtis Rager from JCI, and Paul Scheihing from 50001 Strategies. Internal reviewers included Richard Hart. The authors also gratefully acknowledge the assistance of Jethro Medina from The Chemours Company, who provided external review as well as COP analysis. External review and support do not imply affiliation or endorsement. Lastly, we would like to thank Mariel Wolfson, Camron Assadi, and Ben Somberg for editorial guidance and Ethan Taylor for his help in launching this topic brief.