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Heat Pumping Technologies
MAGAZINE

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Flammable Refrigerants in Heat Pumps: Safety, Standards, and Best Practices

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In this Issue

Welcome to the first issue of 2026 of Heat Pumping Technologies Magazine. This edition is dedicated to the theme of **"Flammable Refrigerants in Heat Pumps: Safety, Standards, and Best Practices"**, one of the most consequential topics shaping the near-term trajectory of the heat pump sector.

As the industry accelerates its transition toward low global warming potential (GWP) refrigerants, flammable working fluids, including hydrocarbons and mildly flammable HFOs, are playing an increasingly central role across residential, commercial, and industrial applications. Their strong thermodynamic performance and minimal environmental impact position them as key enablers of decarbonisation. At the same time, their flammability introduces safety considerations that must be rigorously addressed to support reliable and scalable deployment at every level of the value chain.

This issue places safety at the core, examining how system design, component selection, installation practice, monitoring strategies, and operational procedures can be aligned with existing and emerging standards to mitigate risk without compromising performance. It also addresses how regulatory frameworks, certification schemes, and best practice guidelines are evolving to enable broader market uptake.

In the Foreword, titled *"Flammable Refrigerants in Heat Pumps: Managing Risk in a Rapidly Shifting Market"*, we set the strategic context for this edition, examining the convergence of environmental regulation, refrigerant availability, and safety governance reshaping how the industry approaches flammable working fluids.

Our Column features *"Heat Pumps at the Center of Korea's Carbon-Free Transition"*, offering a national-scale perspective on heat pump policy and deployment in one of Asia's most dynamic energy markets.

Topical Articles

"Experimental Insights into Liquid and Vapor Leakage of R-290" (Esmaeelian et al., KTH Royal Institute of Technology, Sweden) investigates R-290 leakage dynamics under controlled liquid and vapor conditions, demonstrating transient pressure and phase-change effects that current steady-state safety models fail to capture. The findings have direct relevance for charge-limit calculations under IEC 60335-2-89.

"Techniques to Safely and Accurately Characterize the Performance of Flammable Refrigerants" (Barta and Ziviani, Purdue University, USA) documents experimental infrastructure for A3 refrigerant testing at system, component, and fluid level, covering psychrometric chambers, compressor test stands, thermophysical property rigs, and flammability facilities, drawing on experience across North America, Asia, and Europe.

"Chemical Stability Problems of Low-GWP HFO Refrigerants with Polyol Ester (POE) Lubricants" (Ignatowicz et al., KTH Royal Institute of Technology, Sweden) examines degradation mechanisms of R1234yf and R1234ze(E) in combination with POE lubricants under high-temperature aging conditions, identifying moisture-driven and lubricant-driven polymerization pathways validated against samples from real installations.

"Renewable District Heating from a Waste-to-Energy Plant through the Adoption of Large Commercial and Industrial Heat Pumps" (Gandini, Studio Gandini S.R.L., Italy) presents the Brescia WtE plant case study, where nine large heat pumps using R1234ze(E) delivered a 33% increase in thermal output and raised overall plant efficiency from 82% to 98%, without increasing combustion input, a compelling demonstration of HTHP technology and A2L refrigerant deployment at industrial scale.

National Market Section

In our National Market spotlight, we turn to **Switzerland**, presenting an exclusive **Heat Pump Market Report** examining deployment trends, policy drivers, and market dynamics in one of Europe's most advanced heat pump markets.

We trust this issue provides a technically substantive and practically grounded perspective on the state of flammable refrigerants in heat pump technology, and that it serves as a useful reference for all those working to advance safe, efficient, and scalable decarbonisation of heating across all sectors.

Enjoy your reading!
Dr Metkel Yebiyo, Editor
Heat Pump Centre
The central communication activity of the Technology Collaboration
Programme on Heat Pumping Technologies (HPT TCP)

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Foreword

Flammable Refrigerants in Heat Pumps: Managing Risk in a Rapidly Shifting Market

By senior professor Björn Palm, Department of Energy Technology, KTH Royal Institute of Technology, and Operating Agent for HPT Project 64

The topic of this issue of HPT Magazine is Flammable Refrigerants in Heat Pumps. This is a very timely topic as we see the number of products with propane increasing rapidly. According to the Keymark heat pump database, the share of propane-powered products on the EU market rose from 3% in 2021 to 38% in 2024. Statistics on actual sales are not available, but estimates based on subsidy applications in Germany indicate that the market share was about 20% already in 2022. But even if the market for hydrocarbon heat pumps has increased considerably in the last few years, such products have been on the market for a long time. Already in 2008, more than 50 models of hydrocarbon heat pumps were commercially available.

Flammability is not only an issue that needs to be considered for hydrocarbon systems. Most low-GWP synthetic fluids are also flammable, even if the risks are lower. It is therefore important to investigate how systems with flammable refrigerants can be designed to be safe. For heat pumps, there is already the international product standard IEC 60335-2-40, updated in 2024, which can be used as a guideline. In the EU, we are hoping to see a new version of EN 378 shortly. There is also an excellent new book concerning safety with flammable refrigerants, written by Stig Rath and Harald Erös, called *Propane, Naturally Safe!*

To increase safety, it is important to limit the refrigerant charge. With the old HFC and HCFC refrigerants, reducing charge was not important, as a leak was not a threat to the immediate environment. Systems and components were therefore not designed with charge reduction in mind. With flammable refrigerants, we need to think differently. Several research projects have been focusing on this topic, and it has been demonstrated that it is possible to design and run a 12 kW liquid-to-water heat pump with as little as 120 g of propane or isobutane, i.e., 10g/kW. There are several commercial products on the market with capacities of 6-7 kW, having a charge of 152g, i.e., 21-25g/kW. My expectation is that the specific charges will continue to decrease in the coming years.

Other topics related to safety is how to avoid high refrigerant concentrations in case of a leak. What types of leaks can be expected? What is the mass flow of refrigerant through a given hole size? How will this flow develop over time? How much of the refrigerant will leak out? And how can the releasable charge be limited? How can air circulation in the room be maintained to avoid stratification? Answers to these and similar questions are important to be able to design and install safe systems with flammable refrigerants. Research has already given some answers, but more research is needed, and these results need to be used as a basis for updated standards. In the IEA HPT Project 64 on Safety with flammable refrigerants, we are working on these questions and plan to present a final report within a year. Some of this research is presented as thematic articles in this issue of the HPT Magazine.

Finally, the risks of using propane as a refrigerant should be taken seriously, but we have been using this gas as a fuel in our homes for 100 years. It does not become more dangerous in a hermetic heat pump system!

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Column

Heat Pumps at the Center of Korea’s Carbon-Free Transition

By Minsung KIM, Professor, Chung-Ang University, Republic of Korea, ExCo alternate delegate to the IEA HPT TCP

South Korea is entering a major turning point in its energy transition. Until now, national energy policy has largely been shaped by two priorities: expanding carbon-free electricity generation and maintaining a stable power supply. In Korea, carbon-free energy includes both renewable energy and nuclear power, reflecting the country’s broader approach to decarbonization. At the same time, Korea’s isolated power grid and limited external interconnection have made electricity security and peak demand management especially sensitive issues. Under these conditions, the national energy strategy has focused primarily on securing reliable carbon-free power generation, while taking a cautious approach toward large-scale thermal electrification.

This policy direction began to evolve following the launch of the Ministry of Climate, Energy, and Environment in October 2025, which marked an important step toward integrating climate, energy, and environmental policy under a unified governance structure. At the same time, a thermal industry division was established within the ministry, reflecting growing recognition that the thermal sector must become a central part of Korea’s decarbonization strategy. As heating and cooling account for a large share of final energy consumption, transforming thermal energy systems is increasingly seen as a key challenge for achieving carbon neutrality.

A symbolic milestone came on March 10, 2026, when the revised Enforcement Decree of the New and Renewable Energy Act was officially promulgated, formally recognizing air-source heat pump systems within Korea’s renewable energy framework. This was a significant policy shift. Until recently, only hydrothermal and geothermal heat pump systems were institutionally recognized, despite the expanding role of heat pumps in low-carbon energy systems. The inclusion of air-source heat pump systems, therefore, represents more than a technical revision. It signals that Korea is beginning to formally recognize thermal electrification as an important pathway within national carbon-free energy policy.

Attention is now shifting from policy direction to practical implementation. In particular, the large-scale transition from conventional residential boilers to heat pump systems is expected to create substantial impacts not only on the national power grid but also on local distribution networks in residential areas. Domestic hot water demand patterns, which are concentrated during specific hours of the day, could significantly increase localized peak electricity loads if electrification proceeds without careful planning. Even with demand forecasting and load management strategies, increases in electricity demand and additional grid reinforcement will likely be unavoidable. As a result, discussions are increasingly focusing on how thermal electrification can expand while maintaining grid stability and supply reliability.

Challenges still remain, including electricity market reform, grid flexibility, and public acceptance of electrified heating systems. Nevertheless, the overall direction is becoming increasingly clear. Korea is now moving beyond a power generation-centered strategy toward a broader transformation of the entire energy system. The expansion of heat pump-centered policies and the official recognition of air-source heat pump systems within Korea’s renewable energy framework together signal the beginning of a major transition toward a sustainable, carbon-free future.

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Topical Article

Experimental Insights into Liquid and Vapor Leakage of R-290

DOI: 10.23697/ajz3-x954

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Hydrocarbon refrigerants such as R-290 are increasingly used in heat pumps due to their low environmental impact, but their flammability requires accurate leakage modeling. This study investigates leakage behavior under controlled liquid and vapor conditions using a simplified experimental setup. The results show that while liquid leaks initially produce much higher mass flow rates, they decrease rapidly due to pressure drop and cooling, whereas gas leaks persist longer and cause stronger internal cooling. These findings highlight the importance of transient effects and provide valuable input for improving safety models and charge-limit calculations in standards such as IEC 60335-2-89.

Introduction

The increasing adoption of low-GWP refrigerants has accelerated the use of hydrocarbons such as R-290 in heat pumps and refrigeration systems. These refrigerants offer excellent thermodynamic performance and minimal climate impact, but their flammability introduces additional safety considerations.

One of the most critical factors in assessing flammability risk is the rate at which refrigerant is released during a leak. Leakage rate determines how quickly a flammable cloud can form, how large it becomes, and how long it persists. These aspects directly influence safety standards, system design, and charge-limit calculations.

Previous studies have reported differing conclusions regarding the relative severity of liquid and vapor leaks. Some experimental programs have shown that liquid leaks can be significantly stronger due to higher fluid density, while others indicate that system behavior and phase transitions can reduce this difference. These discrepancies highlight the need for a clearer understanding of the underlying leakage mechanisms.

Test Setup and Results

A simplified approach to leakage investigation

To isolate the fundamental physics of refrigerant leakage, a simplified experimental setup was developed, as shown in Figure 1. Instead of testing a complete heat pump system, a dual-cylinder configuration was used to represent the liquid and vapor regions separately. This approach eliminates the influence of system complexity, such as refrigerant migration, internal flow paths, compressor operation, and component interactions, which are known to affect leakage behavior in full-scale systems. Leakage was simulated through small holes located at different vertical positions, corresponding to gas, liquid, and intermediate (two-phase) conditions. The leakage process was monitored by measuring mass loss, pressure, temperature, and surface temperature distribution using infrared imaging. By simplifying the geometry while maintaining realistic thermodynamic conditions, the setup allows the fundamental leakage mechanisms to be studied more clearly than in full-system experiments.

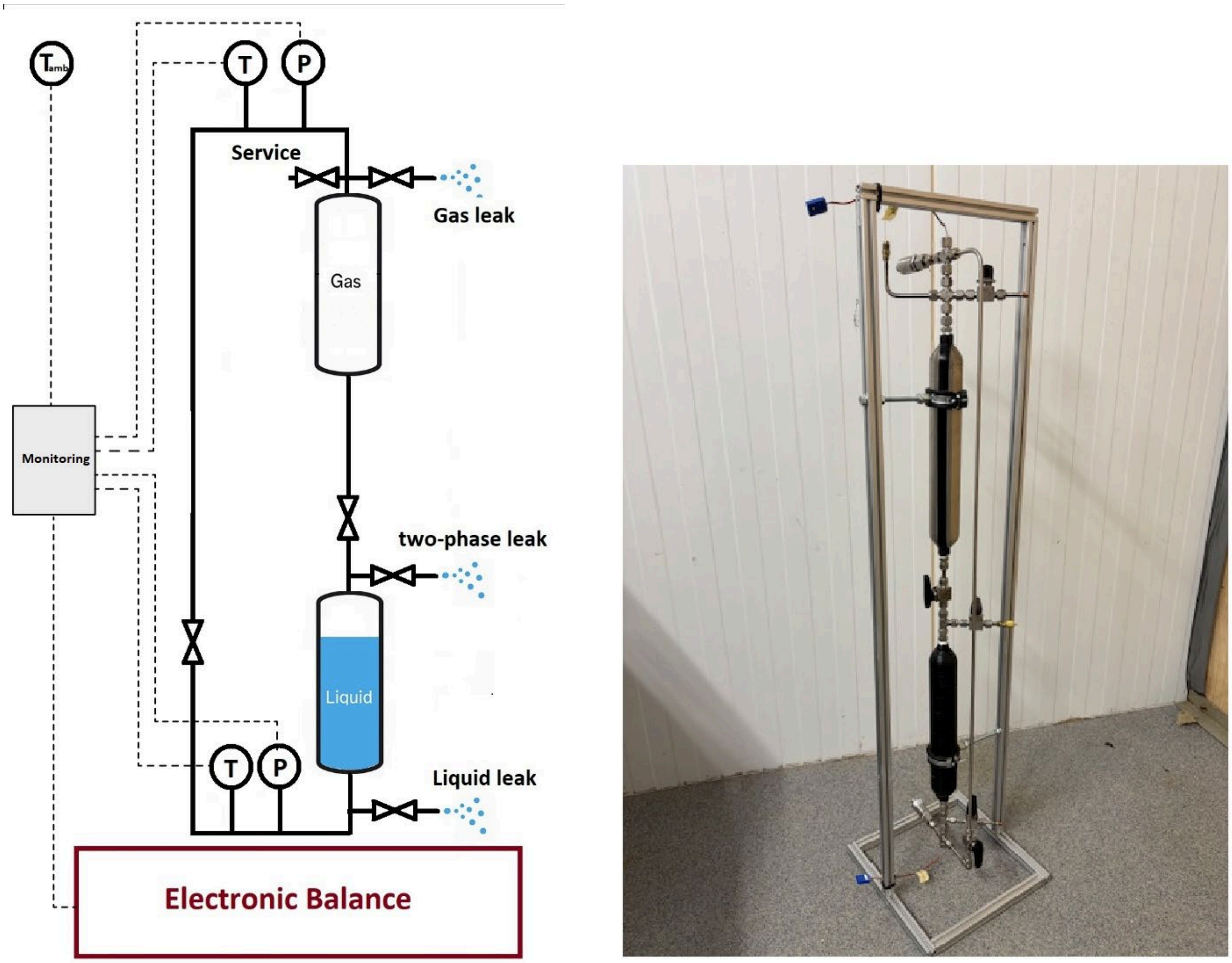

Figure 1: ***Experimental setup schematic and test rig.***

Liquid leaks: high initial discharge but rapid decay

The experiments show that liquid leaks initially produce significantly higher mass flow rates than vapor leaks. This is primarily due to the higher density of liquid refrigerant at the same pressure, consistent with observations reported in large-scale ORNL and AHRTI studies [1]. Under the tested conditions, liquid leakage produced a rapid initial discharge accompanied by a steep pressure drop inside the cylinder. However, this high discharge rate does not persist. As the leakage continues, the system cools rapidly due to evaporation, leading to a decrease in pressure and a corresponding reduction in leakage rate. In addition, a substantial portion of the liquid undergoes flashing at the leak opening, forming a two-phase mixture that reduces the effective discharge density. Similar transient effects have been discussed in previous leakage investigations of hydrocarbon refrigerants [2]. The resulting pressure evolution for liquid and gas leakage conditions is shown in Figure 2. Liquid leakage produces a rapid initial depressurization, while gas leakage results in a slower and more gradual pressure decay.

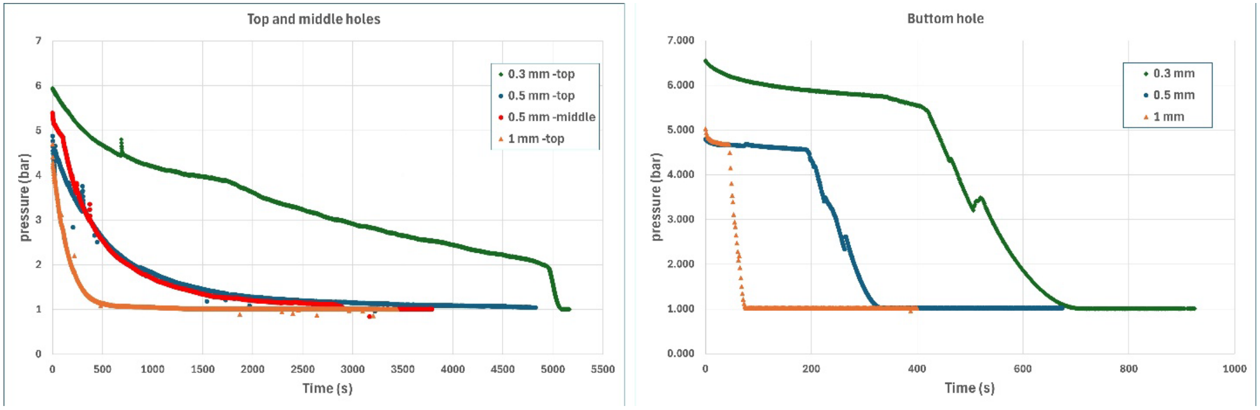

Figure 2: Pressure decay for gas leakage (left) and liquid leakage (right).

Gas leaks: lower intensity but longer duration

Gas-phase leakage behaves differently. Although the initial leakage rate is much lower, the discharge continues over a significantly longer period. This is because the pressure decreases more gradually and the mass flow is limited by compressible-flow effects. An important observation is that gas leaks lead to stronger internal cooling than liquid leaks. This occurs because evaporation predominantly takes place inside the system, continuously absorbing heat from the surroundings. This internal cooling further reduces pressure and progressively slows the leakage process. The cumulative released mass for different leakage conditions is presented in Figure 3. While liquid leaks release refrigerant rapidly during the initial stage, gas leaks continue discharging refrigerant over a much longer period.

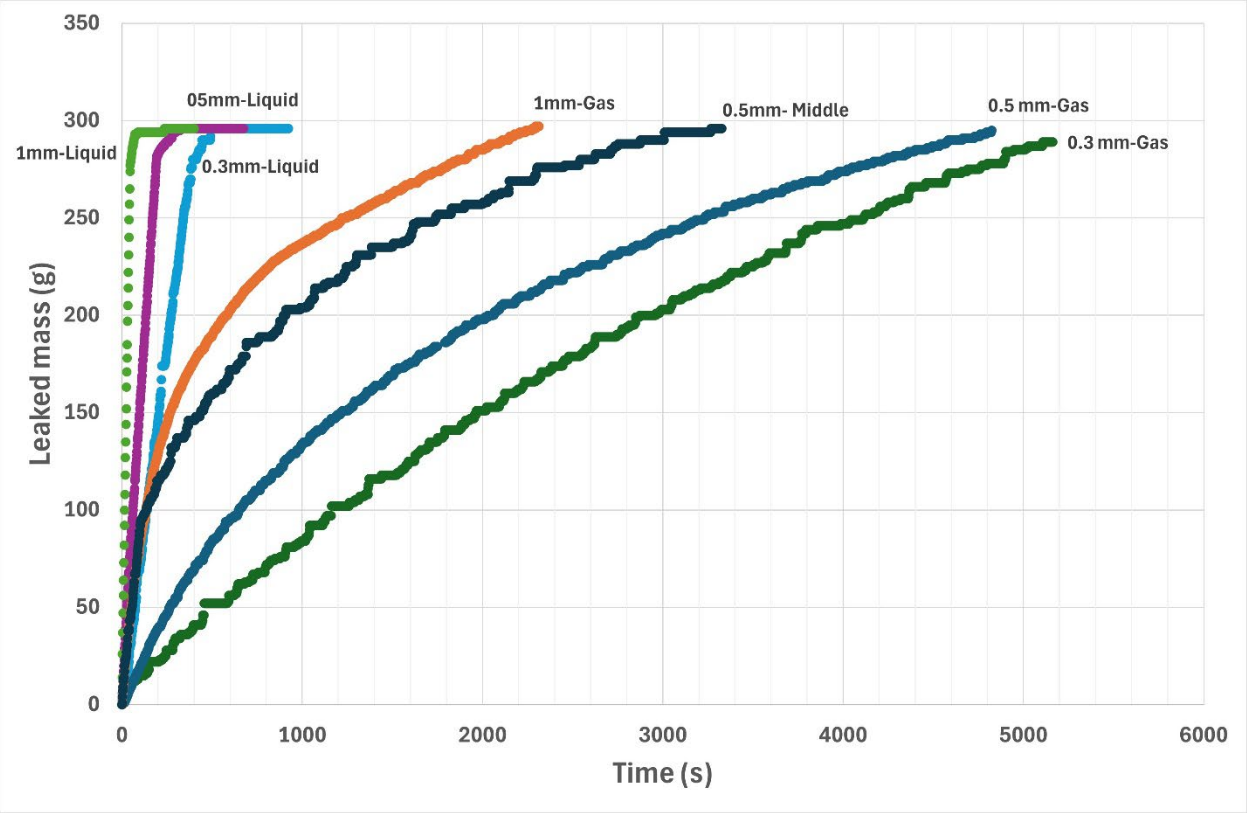

Figure 3. Cumulative leaked mass comparison.

Where evaporation occurs matters

Infrared imaging revealed that the location of evaporation plays a crucial role in determining system behavior, as illustrated in Figure 4. Interestingly, the strongest cooling was not observed directly at the leak hole, but rather near the liquid surface inside the cylinder, where evaporation occurred. For gas leaks, evaporation mainly takes place inside the system, resulting in substantial internal cooling and a strong reduction in wall temperature. In contrast, during liquid leakage, a large portion of evaporation occurs outside the system after the refrigerant exits the orifice. As a result, internal cooling is less pronounced despite the significantly higher initial mass flow rate. These observations demonstrate that leakage behavior is governed not only by pressure and orifice size, but also by the interaction between phase change, evaporation location, and heat transfer.

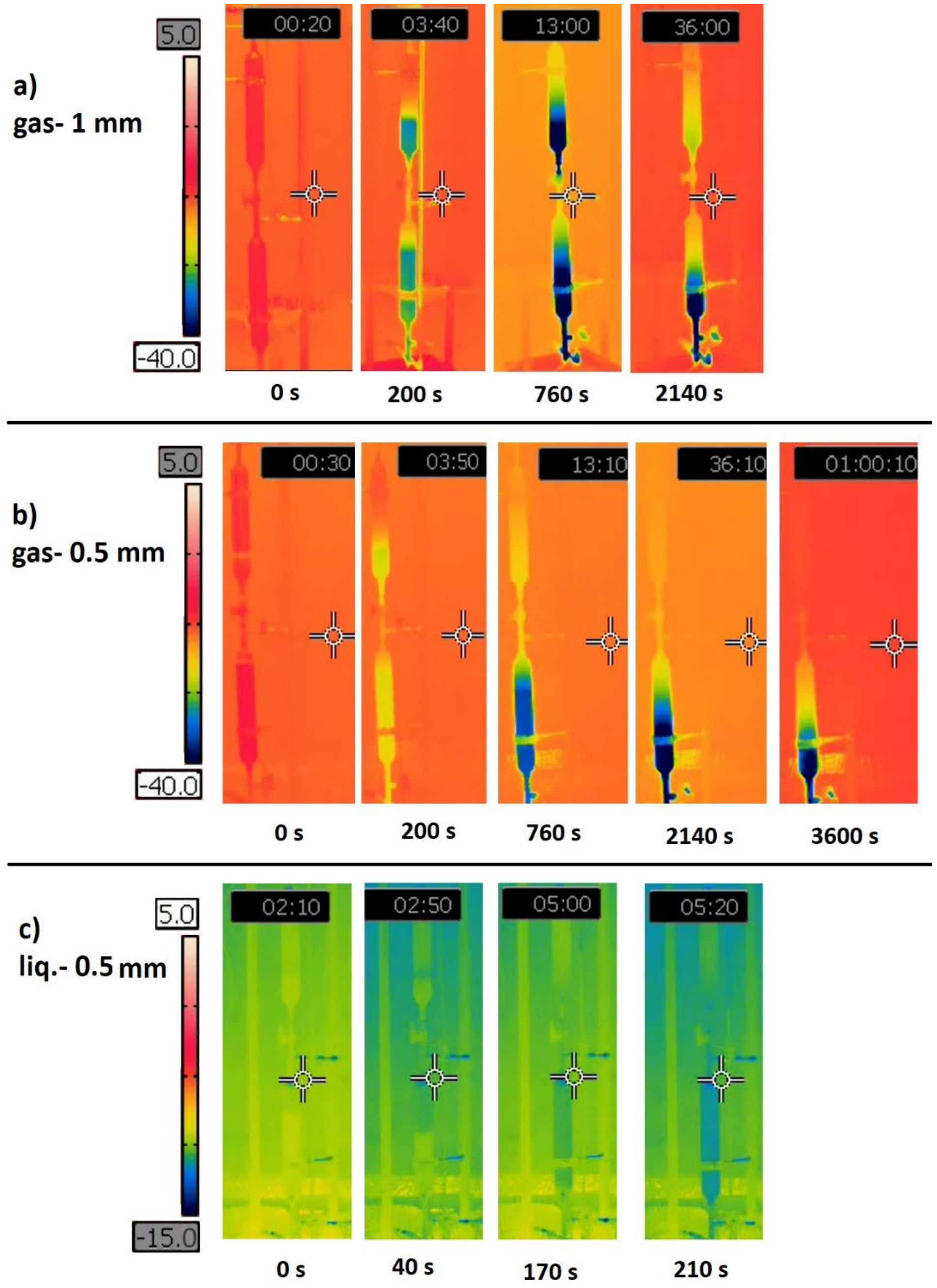

Figure 4. Infrared temperature evolution during leakage.

Limitations of simplified leakage models

Leakage is often modeled using simplified equations assuming constant pressure and steady flow. However, the experiments clearly demonstrate that refrigerant leakage is a transient process influenced by pressure decay, temperature changes, and phase transitions. In particular, the commonly used incompressible liquid-flow model tends to overestimate leakage rates once flashing occurs and the discharge becomes two-phase.

Conversely, compressible choked-flow models provide better agreement for vapor-phase leakage but do not fully capture the early behavior of liquid leaks. These findings suggest that leakage source models used in safety analysis should account for transient thermodynamic effects and phase transitions rather than relying solely on steady-state assumptions.

Implications for safety standards

The present findings have direct implications for safety standards such as IEC 60335-2-89 [3] and for ongoing work within IEA Heat Pumping Technologies Project 64. Current safety calculations often assume constant upstream pressure and simplified leakage behavior. However, the experiments show that pressure decay and internal cooling reduce leakage rates over time compared with constant-pressure assumptions. This means that the duration and magnitude of refrigerant release may be overestimated if transient effects are neglected. A better understanding of leakage dynamics can improve refrigerant leak modeling, leading to more accurate predictions of refrigerant concentration and potentially reducing unnecessary conservatism while maintaining adequate safety margins.

Conclusions

This study demonstrates that leakage behavior of R-290 is strongly dependent on phase conditions, heat transfer, and transient thermodynamic effects. While liquid leaks initially produce higher discharge rates, they decrease rapidly due to pressure reduction. Gas leaks, on the other hand, are less intense but persist longer and result in stronger internal cooling. These findings show that leakage cannot be accurately described using constant-pressure or steady-flow assumptions. Instead, it should be treated as a dynamic process influenced by phase change and energy transfer. The results provide valuable insight for improving leakage models used in safety standards and support ongoing efforts to refine risk assessment methods for flammable refrigerants.

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Topical Article

Chemical stability problems of low-GWP HFO refrigerants with polyol ester (POE) lubricants

DOI: 10.23697/egpr-3t29

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Only chemically stable refrigerants can ensure long lifetime and steady operation. The aim of this paper is to compare lab-controlled chemical stability tests of hydrofluoroolefins (HFOs) at temperatures up to 100ºC for 21days in combination with moisture and polyolester (POE) lubricants against the refrigerant samples from real installations. The results showed that HFOs undergo different polymerization processes in presence of POE lubricants; water; or a mixture of POE lubricants and water. Moreover, the control refrigerant samples showed highly elevated water levels confirming that water is one of the degradation by-products.

Introduction

Currently, mineral oils and semi-synthetic lubricants are not considered suitable for hydrofluoroolefins (HFOs) refrigerants such as R1234yf and R1234ze(E) having zero ozone depletion potential (ODP) and very low global warming potential (GWP). Synthetic lubricants such as polyol esters (POEs), polyalkylene glycols (PAGs), and polyvinyl ethers (PVEs) are increasingly used in the refrigeration and heat pump industry, as safer alternatives to mineral oils [1]. The commercially available POE lubricants are typically composed of linear, branched, or cyclic pentaerythritol esters (PECs) [2]. POE lubricants, due to their high polarity, can exhibit widely varying properties despite having the same viscosity index as mineral oils [3]. It is important to underline that the thermal stability and water absorptivity of different lubricants are of significance since water can accelerate degradation, and water content above 50 ppm should be strictly avoided [2]. Polar lubricants such as PAGs exhibit the highest water absorption among all synthetic oils, whereas mineral oils, due to their non-polar nature, have the lowest water absorption capability. Additionally, the viscosity index of POE lubricants plays a critical role in their water absorption behavior, and products with low viscosity index tend to have higher water absorptivity [4]. According to the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Standard 700-2024, the maximum allowable water content in HFO refrigerants is 20ppm [5].

Synthetic refrigerants can undergo ten different chemical degradation paths: molecular rearrangement, polymerization, hydrodehalogenation, hydrogenation, elimination, oxidation, nucleophilic substitution, electrophilic addition, disproportionation, and pyrolysis. Moreover, the reaction rates for stereoisomer rearrangement (Z to E isomerization) for HFOs were reported to be very low. Nevertheless, operating temperatures above 130°C can cause some isomerization, even in the more stable E-type isomers [6], suggesting a significant application limitation. As found, R1234yf exhibited a significant degradation in the presence of air and water due to hydrolysis of POE lubricant [7]. Studies showed that HFO refrigerants, such as R1234yf and R1234ze(E), in combination with POE lubricants, exhibited lower chemical reactivity than PVE lubricants over 14 days at 175°C [8]. Additionally, the isolated incidents of R1234yf polymerization during charging of mobile air conditioning systems, where “silicone-like” deposits caused irreversible system damage and indicated that probable causes included moisture and elevated temperatures during handling, leading to polymerization. To avoid polymerization, avoiding direct sunlight during transport and storage, slowly opening gas cylinders to prevent pressure changes, and avoiding rubber seals that contain peroxides (recommending PTFE, Teflon) were recommended [9].

Summing up, the literature review on the thermal and chemical stability of R1234yf and R1234ze(E) reported no significant degradation in different HVAC and laboratory experiments, nor signs of polymerization. However, no studies have examined the chemical stability of refrigerants in combination with different POE lubricants using the updated ASHRAE Guideline 38-2023 (Guideline for Using Metal Pressure Vessels to Test Materials Used in Refrigeration System) [10]. Therefore, the aim was to investigate the chemical stability and material compatibility of HFOs with POE lubricants having different chemistry under high-temperature and high-pressure conditions representative for applications, and comparison of obtained degradation results with refrigerant samples from real industrial installations.

Methodology

The compatibility and chemical stability of refrigerants and lubricants were evaluated using specially designed stainless-steel (SS) gas reactors. These tests followed the updated ASHRAE Guideline 38-2023 (Guideline for Using Metal Pressure Vessels to Test Materials Used in Refrigeration Systems). Each gas reactor consists of a cylindrical SS body, two SS ball valves with PTFE sealing and a four-screw closing mechanism (at the valve-cylinder connection edge), allowing for large sample volumes of approximately 99.98±0.1cm^3. ASHRAE Standard 97-2007 (RA 2017) [11] was used for the calculation of refrigerant mass and calibration of the gas reactor volume and pressure sensors. To investigate the effects of lubricant presence and moisture, four sample categories were prepared for each refrigerant:

- Pristine refrigerant control sample (water content <20 ppm)
- Pristine refrigerant (water content <20 ppm) with additized POE lubricant – 1:1 mass ratio
- Pristine refrigerant (water content <20 ppm) with 5000 ppm added water
- Pristine refrigerant (water content <20 ppm) with additized POE lubricant and 5000 ppm added water.

This method enabled the evaluation of lubricant-driven and moisture-driven degradation mechanisms. Given that lubricant viscosity requirements can vary based on operating temperature, two different POE lubricants were tested. The aging and chemical stability experiments were carried out using a Termaks 4000 laboratory oven (temperature accuracy of ±1 °C). The refrigerant chemical composition was validated using a Thermo Scientific Trace 1310 Gas Chromatograph (GC) with Flame Ionization Detection (FID) and Thermal Conductivity Detector (TCD). Moreover, Liquid Chromatography-Tandem Mass Spectrometry (LC-MS/MS) was used to validate the lubricant composition. In addition, the control tests of pristine POE lubricants were conducted at 150°C for 21 days in the oven to assess any potential discoloration or physical degradation. Full details of the testing procedure can be found in [12]. Table 1 summarizes the testing conditions and lubricant Viscosity Index (VI).

Refrigerant	Testing conditions	POE Lubricants
R1234yf	period: 21 days, temperature: 90ºC	POE VI32; POE VI55
R1234ze(E)	period: 21 days, temperature: 100ºC	POE VI55; POE VI85

Table 1: Summary of the testing conditions.

After the 21-day chemical stability tests, the refrigerant samples were carefully separated from other components and transferred to smaller SS gas cylinders for GC analysis and to custom-built sealed glass tubes for visual inspection and expansion, as shown in Figure 1.

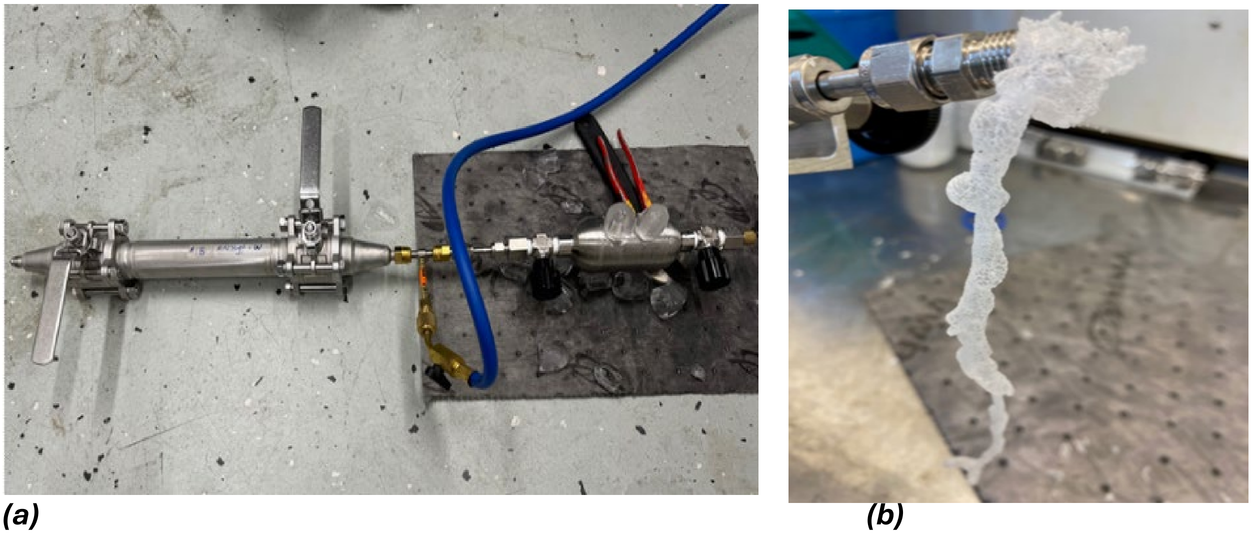
(a) *(b)*

Figure 1: The transfer procedure of thermally treated refrigerant from the gas reactor to a smaller gas bottle for GC analysis (a), polymer-like formation during expansion test from the sealed glass tubes (b).

Results

Firstly, a pristine commercial POE lubricant composition was analyzed to quantify the relative fractions of linear and branched esters to understand the possible chemical interactions with the refrigerant. Table 2 presents the results of the analysis of the pristine lubricant composition.

Sample	Penta-esters [%]	Dipenta-esters [%]	Additives / Stabilizers [%]
POE VI32	53	47	-
POE VI55	4	95	1
POE VI85	32	67	1

Table 2. Commercial POE lubricant composition analysis

Notably, one lubricant exhibited absent levels of stabilizing organophosphorus additives, which may reduce resistance to thermal or chemical degradation under high-temperature conditions. Tables 3 summarize the chemical stability results for both refrigerants.

Refrigerant	Pristine refrigerant	Refrigerant with POE lubricant	Refrigerant with water	Refrigerant with POE lubricant and water
R1234yf	No reaction	No reaction with POE VI32; **White porous polymer** (foam type) with POE VI55;	**White porous polymer** (foam type);	**Transparent gel,** smelly sample with both POE lubricants;
R1234ze(E)	No reaction	POE VI55: **small white hard particle** in gas reactor, **whitish gel** in glass tube, smelly sample; POE VI85: **whitish gel** in glass tube, smelly sample, no particle;	No reaction	**Hard particles in whitish dense gel in both cases,** smelly sample in both cases;

Table 3. Summary of chemical stability results for HFO refrigerants.

As shown in Table 3, both HFO refrigerants appear to be highly thermally stable when pristine samples with water content below 20 ppm were analyzed. R1234yf was very stable with POE lubricant VI32, having less branched dipenta-esters. Instead, R1234yf with POE VI55 (recommended for higher temperatures) was very unstable and polymerized after the 21-day test. Moreover, R1234yf exhibited pronounced instability in the presence of both water and

POE lubricants, resulting in a new liquid gel-type product. These findings are similar to results reported for R1234yf and three different POE lubricants [13], suggesting that the ratio between the branched dipenta-esters and penta-esters needs to be properly selected to reduce the risk of chemical degradation of R1234yf. A similar degradation path was observed for R1234ze(E) in contact with POE lubricant and water, whereas the control thermally treated refrigerant sample showed no signs of polymerization. Instead, tests conducted with two POE lubricants having a higher share of dipenta-esters showed very high chemical instability and a new gel-type product in the sealed glass tube expansion test. Furthermore, in the case of the test R1234ze(E) with POE VI55 lubricant, small, sharp white polymer-type particles were obtained (shown in Figure 2a).


(2.a) (2.b)

Figure 2. R1234ze(E) with POE VI55 lubricant (a), R1234ze(E) with POE lubricant and water polymerization product.

Moreover, similar hard particles in a white dense gel (shown in Figure 2.b) were obtained in the test with POE lubricants and excess water. In these cases, it was impossible to separate the lubricant or water from the gel formation. Finally, R1234ze(E) did not show any chemical instability when exposed to high water levels. As seen in Tab.3, both HFOs showed a specific chemical instability that was never reported before. The observed polymeric formations are most likely derived from fluorinated refrigerant species [6,13], as POE lubricants do not polymerize [14]. Since the polymerizing refrigerant can cause damage to the GC instrument, it was decided to only test the control refrigerant samples that were not showing any signs of polymerization. In the case of thermally treated R1234yf sample, neither chemical degradation nor new unidentified peaks were detected using the TCD. The GC analysis of R1234ze(E) revealed more unexpected results. The pristine R1234ze(E) tests confirmed lower purity refrigerant (about 96.64% pure) and some impurities such as R1234yf, water, 2 unknown substances, and two non-combustible gases (oxygen and carbon dioxide). Instead, the thermally treated R1234ze(E) sample exhibited a substantial increase in water content, reaching approximately 852ppm (roughly 26 times higher than in the pristine sample), suggesting that water can be one of the by-products from R1234ze(E) degradation (shown in Figure 3).

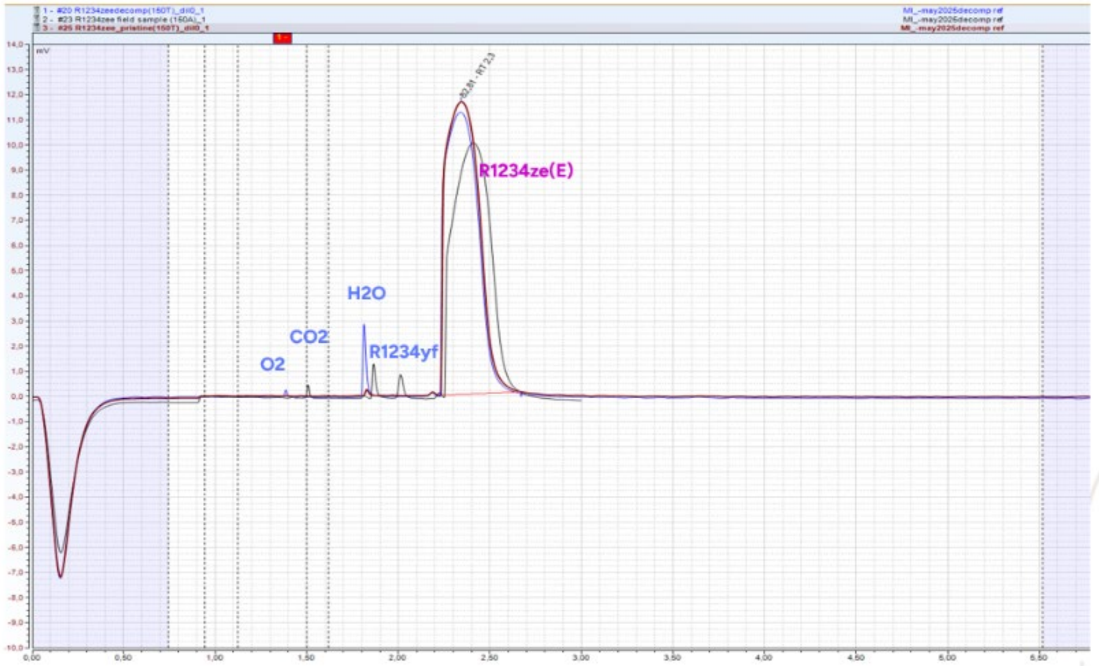

Figure 3: Comparison of TCD results for three R1234ze(E) samples.

Moreover, R1234ze(E) sample from an industrial installation (the black chromatogram) showed similar tendency and alarming high water levels that confirms the chemical instability of R1234ze(E). Note that no degradation models for HFO refrigerants were found in open literature, except for one atmospheric degradation model for R1234ze(E) [15], which identifies water as one of the final products.

Conclusions

This study showed that some HFOs are very sensitive to POE lubricant composition with a higher share of dipenta-esters. The key novelty of this work lies in the direct comparison between laboratory-controlled chemical stability tests and refrigerant samples from a real industrial installation. As found, different parameters such as moisture content and lubricant can trigger polymerization processes that can lead to significant system failure. Each refrigerant seems to form different polymer structures. This study confirms that water is one of the final degradation products, which can cause further degradation of the lubricant and R1234ze(E) polymerization.

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These should be kept to a minimum and indicated numerically, e.g.:

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Topical Article

Techniques to Safely and Accurately Characterize the Performance of Flammable Refrigerants

DOI: 10.23697/2emm-tg04

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As hydrocarbon refrigerants continue to gain popularity for vapor-compression cycle applications, a safe and reliable research and development infrastructure for testing A3 refrigerants and their systems becomes critical. This article will provide background and examples for experimental infrastructure designed to characterize systems and components using A3 working fluids, as well as the fluids themselves. Applications range from ultra-low-temperature refrigeration to high-temperature heat pumps, and perspectives from North America, Asia, and Europe are offered.

Motivation for the Use of Flammable Refrigerants

As refrigerant phase-outs and increasingly scrutinizing environmental legislation continue to gain momentum around the world, vapor compression cycle developers find themselves with two primary paths to regulatory compliance: low-Global Warming Potential (GWP) synthetic refrigerants, such as Hydrofluoroolefins (HFOs) and mixtures of HFOs and

Hydrofluorocarbons (HFCs), or the so-called natural refrigerants, such as hydrocarbons, carbon dioxide, water, and air. In addition to GWP, another key characteristic of these refrigerants is their flammability, which is generally classified according to ISO 817 [1] or ASHRAE 34 [2]. *A* is less toxic, and *B* is more toxic; 1 has no flame propagation, 3 is extremely flammable, 2 is generally flammable, and 2L is mildly flammable, with a burning velocity under 10 cm/s. The reasons for selecting flammable or non-flammable, synthetic or natural materials are debated and largely depend on the application and the trade-offs between volumetric capacity (i.e., heat exchanger and compressor sizing requirements) and GWP [3].

With respect to methods of characterizing thermal systems, the scope of this article will focus on vapor compression cycles, including ultra-low temperature (ULT) applications (e.g., vaccine cooling), domestic and industrial refrigeration, and heat pumps ranging from cold climate (e.g., ambient temperatures below –20 °C) all the way to high-temperature heat pumps (e.g., providing heat at 200 °C). Full system characterization is often carried out via psychrometric chambers to simulate the targeted airside. Compressor characterization is often conducted using a calorimeter or a hot-gas bypass test stand, while heat exchanger characterization can be performed in smaller test loops, depending on the secondary fluid type. At the fluid level, thermo-physical property measurements, development of the so-called Daniel Plots relating density, viscosity, and vapor pressure, and flammability tests are of primary interest. While this list isn't exhaustive, it captures the majority of standard test stand types for vapor compression cycle applications.

Given the legislative and market developments driving the development of vapor compression cycles with low-GWP refrigerants, there is a need to openly share infrastructure development techniques for the characterization of hydrocarbon and A3 refrigerants to safely and sustainably drive research and development in this field forward. In this context, this article will focus on the development of experimental infrastructure specifically designed for carrying out system, component, and fluid characterization of A3 refrigerants. The theory behind safety standards will be summarized, with concrete examples provided.

Development Experimental Test Infrastructure

Charge Calculations

The first step in developing any experimental infrastructure to characterize flammable or toxic refrigerants is to understand (a) the safety classification of the working fluid via ISO standard 817 or ASHRAE standard 34 and (b) to determine the amount of charge (mass or refrigerant) the space where the investigation is to take place can safely accommodate via ISO standard 5149 [4] or ASHRAE standard 15 [5]. The nuances of the charge determination are numerous and depend on factors such as the space designation (e.g., is it publicly accessible or accessible only to trained personnel?) and the so-called Refrigerant Concentration Limit (RCL). The RCL represents the maximum refrigerant concentration necessary to create a dangerous atmosphere, whether via flammability (where the Lower Flammability Limit (LFL) is the determining factor) or toxicity (where the Acute Toxicity Exposure Limit (ATEL) is the determining factor). It should be noted that, depending on space classification, various fractions of the LFL can be considered limiting. For example, in the open laboratory settings reviewed here, the authors set the RCL to the conservative limit of 25% LFL or the ATEL, whichever was lower. Once the RCL has been determined, the volume of the space is used to determine the allowable charge. It cannot be emphasized enough that this description is meant to be a general overview of the process, not a fixed rule and calculation, and that each and every experimental setup and design should be designed per the applicable safety standards.

System Characterization

For vapor compression cycles that utilize air as the heat sink, heat source, or both, testing infrastructure is required to vary air temperature and humidity and characterize system performance across a range of controlled operating conditions. This infrastructure is generally referred to as a psychrometric chamber. In regions of the world where air is used as both the source and sink, such as North America, split systems and mini-split systems used in southern Europe and Asia, a pair of psychrometric chambers is often desired to simultaneously control indoor and outdoor conditions seen by the vapor compression cycle. In parts of the world that use air as the heat source and to heat a water circuit, such as central and northern Europe, only one chamber is needed.

To test A3 refrigerants in psychrometric chambers, further considerations are needed in addition to concentration calculations, as the internal volume of the chambers is generally quite small, such that a potentially dangerous concentration of A3 refrigerant could accumulate with a charge lower than necessary for larger vapor compression systems (e.g., residential heat pumps). Therefore, additional calculations based on the required airflow rate to reduce the charge concentration within a given time are necessary. Furthermore, surface temperatures of heating elements need to be checked and often reduced via sheaths to ensure the surface temperatures remain below the lowest auto-ignition temperature of the proposed A3 fluids to be tested. While Propane’s auto-ignition temperature is approximately 470 °C, n-Pentane’s auto-ignition temperature of 260 °C can present notable challenges in this respect. Finally, refrigerant leak sensing to sound an alarm and automatically engage emergency ventilation, static-electricity-reducing bracelets, and documentation of refrigerant charges in systems are among the necessary additional measures.

To provide a concrete example, Figure 1 shows a photo of the pair of A3 psychrometric chambers located at the Ray W. Herrick Laboratories. These chambers have been modified with all of the measures described in the previous paragraph and can safely test systems with approximately 3.2 kg of Propane and nominal capacities 15 kW, with temperatures and humidities ranging from -20 °C to 52 °C and 25% - 95%, respectively [6]. The lessons learned and best practices from this modification process are summarized in Dhillon et al. [7]. Furthermore, an example of a cold-climate heat pump connected to glycol-based secondary loops for testing below -25 °C start-up conditions using a multi-stage propane vapor-compression cycle is provided in Figure 2 to illustrate the diverse testing capabilities [6,7].

Figure 1: Pair of A3-certified psychrometric chambers at the Ray W. Herrick Laboratories

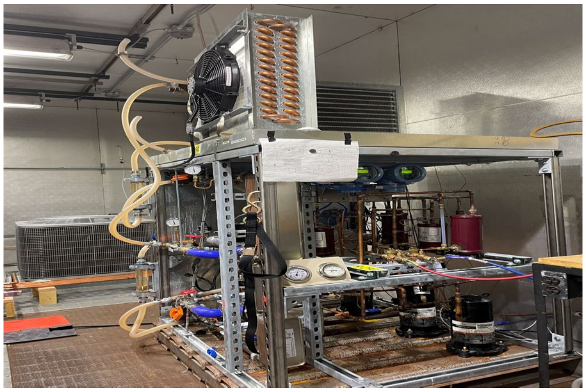


Figure 2: Propane cold climate heat pump situated in A3 psychrometric chambers at the Ray W. Herrick Laboratories

Compressor and Heat Exchanger Characterization

For compressor and heat exchanger testing using A3 refrigerants at the Ray W. Herrick Laboratories, the RCL method determined the allowable test stand charge. Two examples are hot-gas bypass test stands and two-phase pumped loops for compressors and heat exchangers, respectively. These test stands enable efficient, fast characterization of component performance. Key points here were to ensure that any sources of sparks were eliminated from the test stand and that the room volume where the test stands are situated allows for a meaningful A3 refrigerant charge, assuming a 25% LFL limit. An example of a pumped two-phase loop designed to measure composition shifts in working-fluid mixtures, with removable test sections for gas chromatography, is shown in Figure 3 [8].

Figure 3: A3-certified two-phased pumped loop for composition shift and heat transfer measurements, located at the Ray W. Herrick Laboratories

Fluid Characterization

At the fluid level, two primary experimental setups have been developed at the Ray W. Herrick Laboratories. The first focuses on thermophysical property characterization of refrigerant mixtures with and without compressor lubricants, and the second on the experimental characterization of refrigerant flammability.

The thermophysical properties that can be measured are vapor pressure, density, viscosity, and speed of sound. Measurements can be taken from -80 °C to 190 °C, and the pump motor and other electronics are therefore located outside of the chamber to ensure that the refrigerant circuit remains inside the chamber [9]. High-temperature, non-sparking cables and connectors were selected, and stainless-steel sheaths were used to cover wires to sensors that didn’t offer non-sparking models. As with the psychrometric chambers, the chamber in which the thermophysical property measurement circuit is placed has sheaths on the heating elements to make sure that the surface temperature remains below the auto-ignition temperature of the A3 refrigerants to be tested. The temperatures and pressures over which select thermophysical properties can be reliably measured is provided in Figure 4.

Due to the relatively small volume of the chamber, it was decided that excess nitrogen should be pumped into the chamber to prevent the atmosphere from combusting upon a sudden release of charge. To mitigate combustion risks associated with flammable refrigerant leaks, the experimental chamber was maintained as an inert environment throughout the duration of testing. According to safety standards established by the National Fire Protection Association (NFPA 69, Annex C) [10], each flammable refrigerant is characterized by a Limiting Oxygen Concentration (LOC), below which combustion cannot be sustained when an inert diluent such as nitrogen (N_2) is used.

The chamber is equipped with a dedicated nitrogen inlet port connected to a nitrogen cylinder; the nitrogen purge flow is regulated using an inline rotameter, while an electronically actuated solenoid valve provides on/off isolation of the nitrogen supply. Because the chamber is not perfectly leak-tight, oxygen ingress occurs gradually over time. The rate of oxygen concentration increase was experimentally characterized over defined intervals using the oxygen sensor. In parallel, the nitrogen flow rate required to restore the oxygen concentration to the desired level was quantified. This information was then used to establish a controlled purging schedule, allowing estimation of both the frequency and duration of nitrogen charging required to maintain safe operating conditions. If required, this process can be automated through a LabVIEW-based control scheme to maintain a consistently inert atmosphere. Based on this approach, periodic nitrogen purging was implemented to maintain the oxygen concentration within a conservative range below the LOC. This inerting protocol is particularly critical during low-temperature operation (e.g., below −40 °C), where thermal contraction of sealing materials and metallic components increases the likelihood of refrigerant leakage. Furthermore, system overpressurization was addressed by a high-pressure relief valve (PRV) that discharged directly into an evacuated recovery cylinder rather than into the lab space.

A schematic of the property measurement setup is provided in Figure 5.

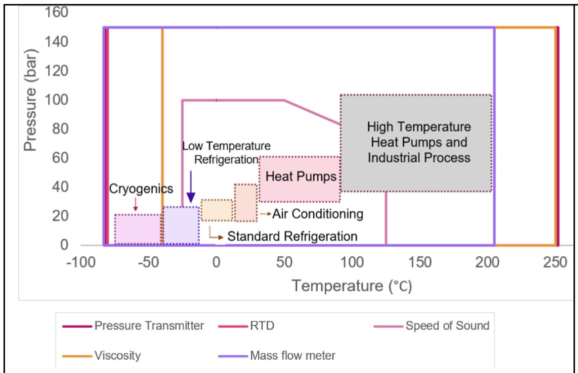
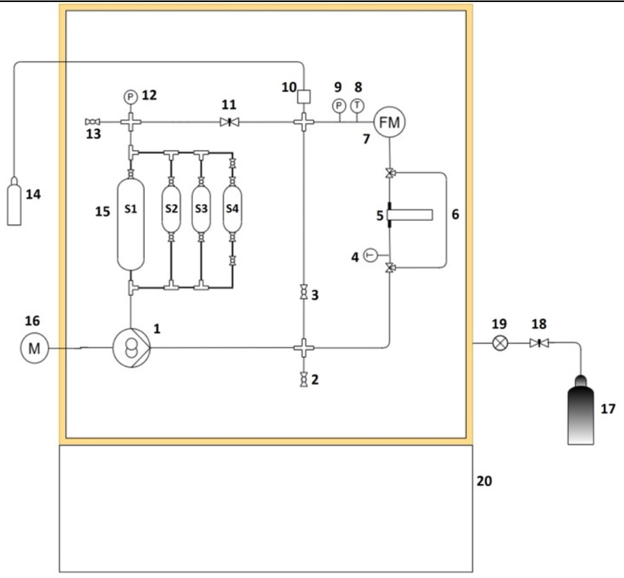


Figure 4: Range of temperatures and pressures associated with thermophysical property measurements.



1. Gear pump, 2. Charging port,3. By pass valve, 4. Temperature sensor, 5. Viscometer, 6. Viscometer bypass section, 7. Coriolis mass flow meter, 8. Temperature sensor, 9. Pressure sensor, 10. Pressure relief valve, 11. Needle valve, 12. Pressure sensor, 13, Charging port, 14, Evacuated recovery cylinder, 15. Cumulative sample cylinder section, 16. gear pump motor, 17. Nitrogen cylinder, 18. Solenoid valve, 19. Rotameter, 20. Environmental Chamber

Figure 5: Schematic of A3-certified thermophysical property measurement setup located at the Ray W. Herrick Laboratories.

Flammability Characterization

Along with property evaluations and both component- and system-level investigations, it is important to understand the flammability behavior of both pure refrigerants and their mixtures. To this end, two sets of experimental facilities have been developed to support the research surrounding ignition sources, flame propagation, sensing and safety, the effect of lubricants, additives, and secondary fluids, among others. The ASHRAE Standard 34 classifies a refrigerant's flammability by using the ASTM E681-09 (Standard Test Method for Concentration Limits of Flammability of Chemicals) test setup [11]. As illustrated in Figure 6(left), the flammability test takes place in a 12-liter glass flask in which a mixture of refrigerant and air is introduced, and a small spark between electrodes causes the mixture to ignite. The flammability is determined with respect to a cone angle of 90°. While this is a standardized test method, it often does not reflect real-life conditions. To this end, 250-liter blast chambers is also utilized to conduct larger-scale flammability tests [12]. As shown in Figure 6(right), the spherical chamber located at the Zucrow Laboratories is air-tight with various optical access ports to visualize the flame front from different angles and enable laser spectroscopy techniques to be applied to measure byproducts.

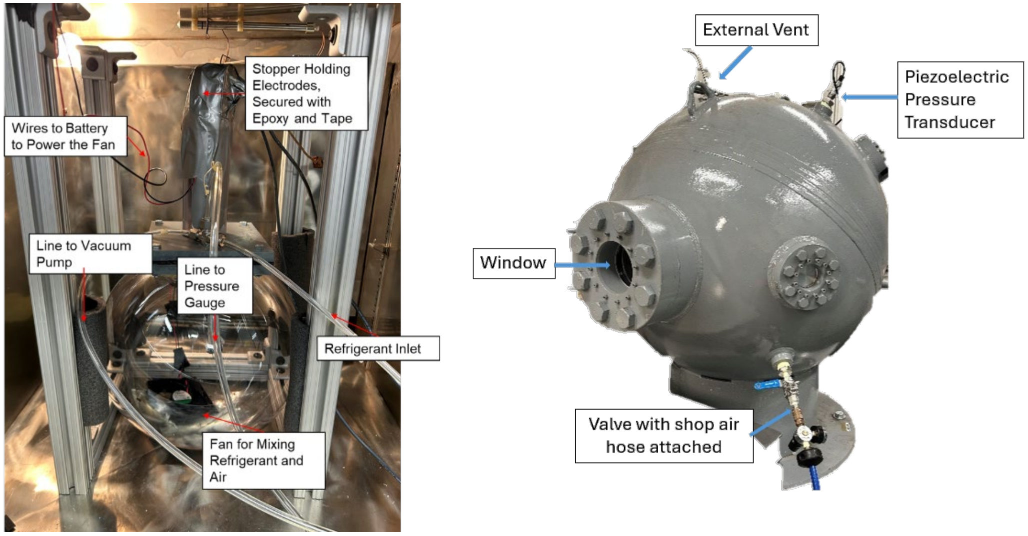


Figure 6: (left) View of the 12-liter flask for the ASTM E681-09 method of test inside a controlled chamber. (right) Blast chamber modified for use in testing refrigerant flammability limits.

These facilities enable quantitative assessments of the flammability characteristics of the refrigerant blends that will inform future standards, building codes, and OEMs. Figure 7 illustrates an ignition sequence of 1 gram of Propane after ensuring well mixing with the internal fan. Whereas Figure 8 shows a similar ignition pattern for Propane, within the larger blast chamber.

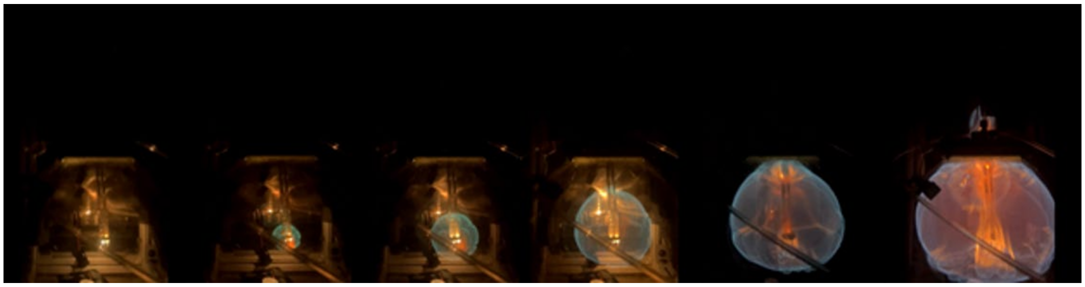


Figure 7: Ignition sequence of Propane (R-290) in the ASTM E681-09 flask.

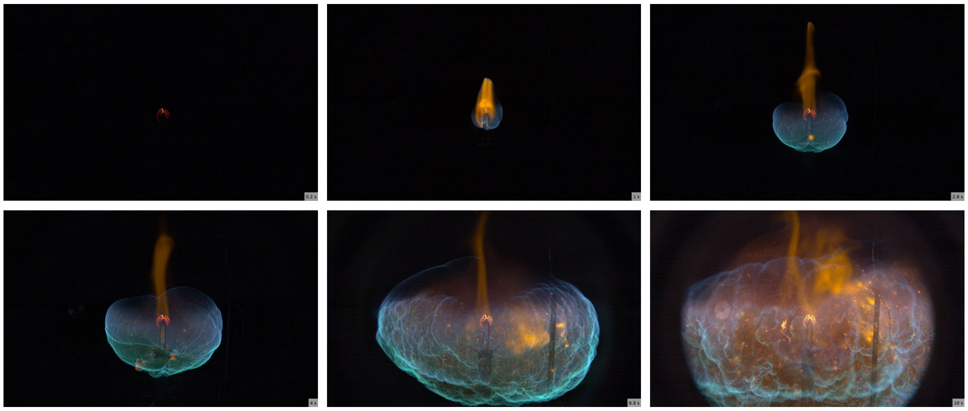


Figure 8: Ignition sequence of Propane (R-290) in the blast chamber

Conclusions

This article provided background and a detailed overview of experimental methods for safely and accurately characterizing A3 refrigerants, their mixtures with lubricants, and the components and systems in which they are used. When the appropriate safety standards are considered, accurate characterization of A3 fluids, components, and systems can be achieved. While research in this space continues to gain momentum, further efforts are needed to develop safety standards for end applications and building codes to broaden acceptance of thermal systems using A3 refrigerants.

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Topical Article

Renewable district heating from a waste to energy (WtE) plant through the intelligent adoption of Large Commercial & Industrial Heat Pumps (LCIHP)

DOI: 10.23697/mvp2-2v32

Jacques Gandini, Managing Director of Studio GANDINI S.R.L., the Italian independent consulting company specialized in residential, commercial, and industrial heat pumps

Heat Pump Technologies (HPT) are considered a valuable solution to provide, at the same time, low primary energy consumption and large usage of renewable energy in all sectors: residential, commercial, and industrial, including the use as a heat source of waste heat coming, for example, as an undesired consequence of Industrial Processes or Data Centers' heat rejection into the atmosphere.

Waste heat in a waste-to-energy plant, instead of being discharged into the atmosphere, can be efficiently used as a heat source by large industrial heat pumps, implementing new generations of heat recovery systems, such as those obtainable through the now mature HTHP (High Temperature Heat Pumps) & VHTHP (Very High Temperature Heat Pumps).

The specific application discussed in this paper is the Brescia (Italy) waste-to-energy plant, where, thanks to the thermal recovery achieved with high-temperature heat

pumps, has been able to increase its thermal output capacity by +33% (a remarkable 60 megawatts more, in addition to the 180MW of the existing plant) and its overall energy efficiency increase by +20%, while maintaining the same combustion level of the existing waste-to-energy system.

A perfect example demonstrating how thermal heat recovery using large high-efficiency heat pumps, in combination with industrial combustion plants, even large-scale ones, is already possible with existing technologies.

Introduction

Between 2010 and 2025, following decades of focus on energy efficiency in residential and commercial buildings, the industrial sector has increasingly emerged as the next major frontier for energy recovery and decarbonisation in Europe. Process heating alone accounts for approximately 32% of total industrial energy use, around 2000 TWh, a scale comparable to residential space heating, yet progress in industrial efficiency has lagged significantly behind (See Figure 1).

A key reason is that industrial processes, with their primary focus on production output, have historically tolerated large quantities of thermal waste, heat that is generated as an unavoidable by-product and then simply discharged to the atmosphere. This is increasingly unacceptable given the ambitions of the EU Energy Performance of Buildings Directive (EPBD IV) [1] and Renewable Energy Directive (RED III) [2], and the broader drive to minimise primary energy consumption across all sectors.

Heat pump technologies offer a direct solution. By upgrading waste heat that would otherwise be lost, Large Commercial and Industrial Heat Pumps (LCIHP) can simultaneously reduce primary energy consumption and increase the share of renewable energy in industrial thermal supply. In the industrial context, three categories are relevant: conventional heat pumps (up to approximately 80°C), High Temperature Heat Pumps (HTHP, up to 100°C), and Very High Temperature Heat Pumps (VHTHP, exceeding 160°C). The Brescia waste-to-energy plant case study presented in this article demonstrates what is already achievable today using mature HTHP technology at scale.

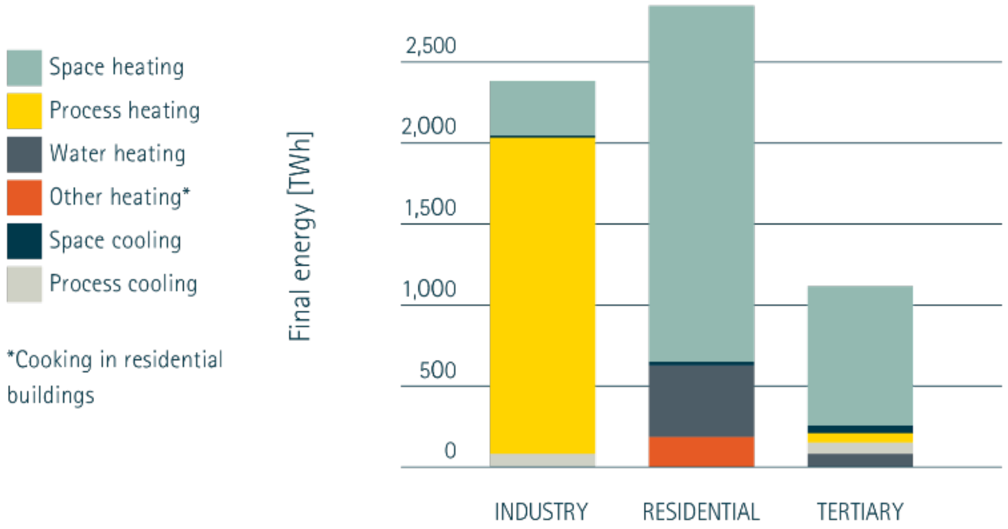

Figure 1: Energy usage distribution by application area, information from the document "Integrating technologies to decarbonize heating and cooling," a publication produced by the European Copper Institute with the contribution of the Fraunhofer Institute and in collaboration with EHPA (European Heat Pump Association) [3]

Large heat pumps, waste-to-heat application

The Brescia (Italy) waste-to-energy (WtE) plant is one of the largest in Italy, producing 60% of the heat required by the city's district heating network.

In 2024, a very innovative project aimed to optimize the flue gas treatment system, reducing nitrogen oxide (NOx) emissions and increasing the energy efficiency of heat production for the district heating network.

The project involved the installation of 9 JCI Johnson Controls heat pumps with centrifugal compressors to recover waste heat from the flue gases of the waste-to-energy plant and produce hot water up to 85°C for district heating.

The intervention included the expansion of the plant with a new flue gas treatment system to be integrated into the combustion line, aiming to reduce NOx and SOx emissions.

The low-temperature heat recovered from the exhaust gases (45/30°C) powers the JCI Johnson Controls heat pumps to produce 60 MW of thermal capacity of hot water (at a nominal temperature of 80°C) for district heating (maximum design water temperature 85°C, PN20).

The installation consisted of 3 trains, each with 3 units in series and counter-series for both the evaporator and the condenser. This setup increases efficiency by dividing the COP across the three units.

Additionally, this type of solution is highly flexible, allowing for maximum versatility in the system with high performance even under varying temperature and load conditions, allowing a nominal system COP of 5,2.

The units use low GWP (Global Warming Potential) refrigerant HFO-R1234ze, with a GWP of 7 and classified as A2L. A thorough risk analysis study was conducted in order to properly manage the mildly flammable refrigerant, in accordance with the EN 378 standard, implementing the correct precautions on-site.

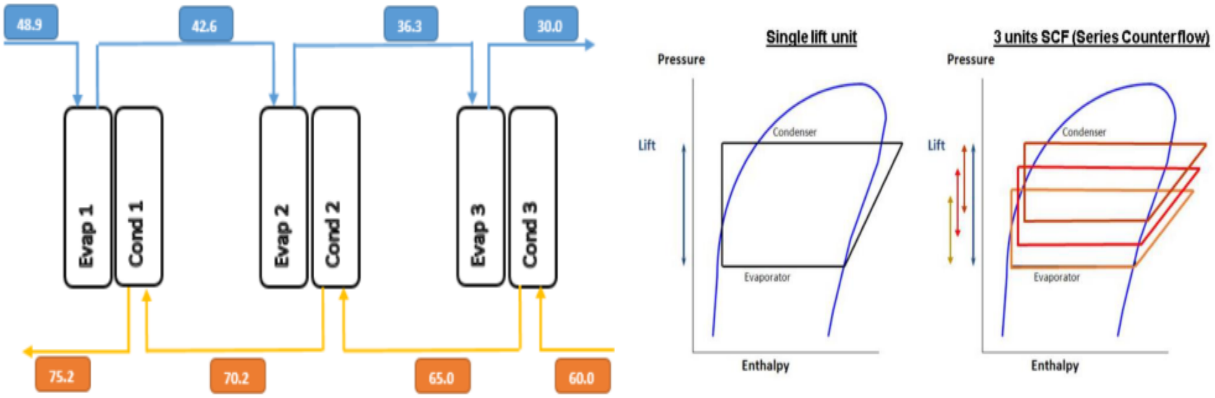

Figure 2: Scheme of interconnection of the 3 Heat Pump units in series and counter-series and relative Mollier diagrams with multiple compressors.

Figure 3: The Brescia (Italy) waste-to-energy plant is one of the largest in Italy. In the picture are represented 6 (of the total 9) Large Heat Pumps to recover the heat from the flue gases of the waste-to-energy plant, with a total heat recovery capacity of 60 MW.

The result obtained, thanks to the energy efficiency intervention involving the installation of 9 Large Capacity Heat Pumps, permitted the plant's generation capacity to increase from 180 MW (ensured by the cogeneration system) to 240 MW (+33%), as shown in Figure 4.
This +60 MW gain was achieved through the recovery of the latent heat from flue gas condensation in addition to the contribution of the 9 Large Capacity Heat Pumps.

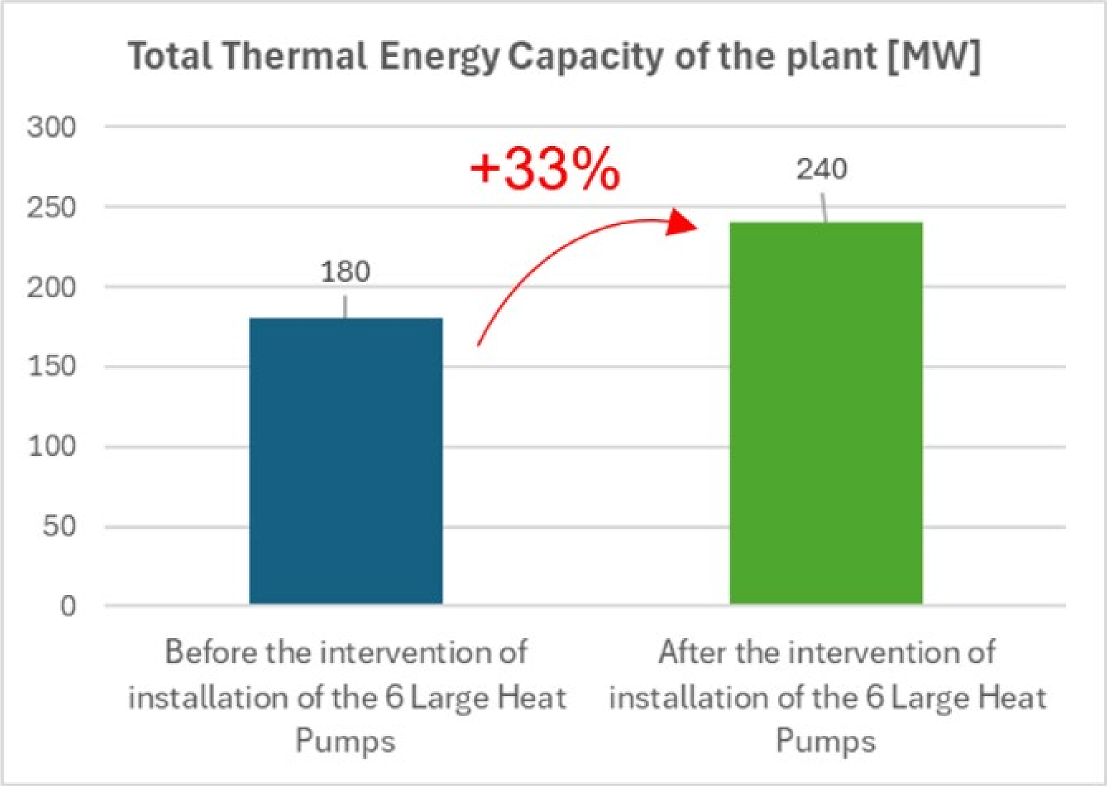

Figure 4: Simplified, non-exhaustive, example of the main results obtained, in terms of energy efficiency, in the Brescia (Italy) waste-to-energy plant, thanks to the introduction of 9 Large Heat Pumps to recover the heat from the flue gases, without increasing the combustion source.

This intervention represents a major advancement in energy efficiency, allowing for a significantly greater recovery of energy without increasing the combustion source. In essence, more useful energy is extracted from the same amount of primary energy input. As a result, the overall efficiency of the plant has improved from approximately 82% to about 98% (+20%) when operating in maximum heat recovery mode, as expressed in Figure 5.

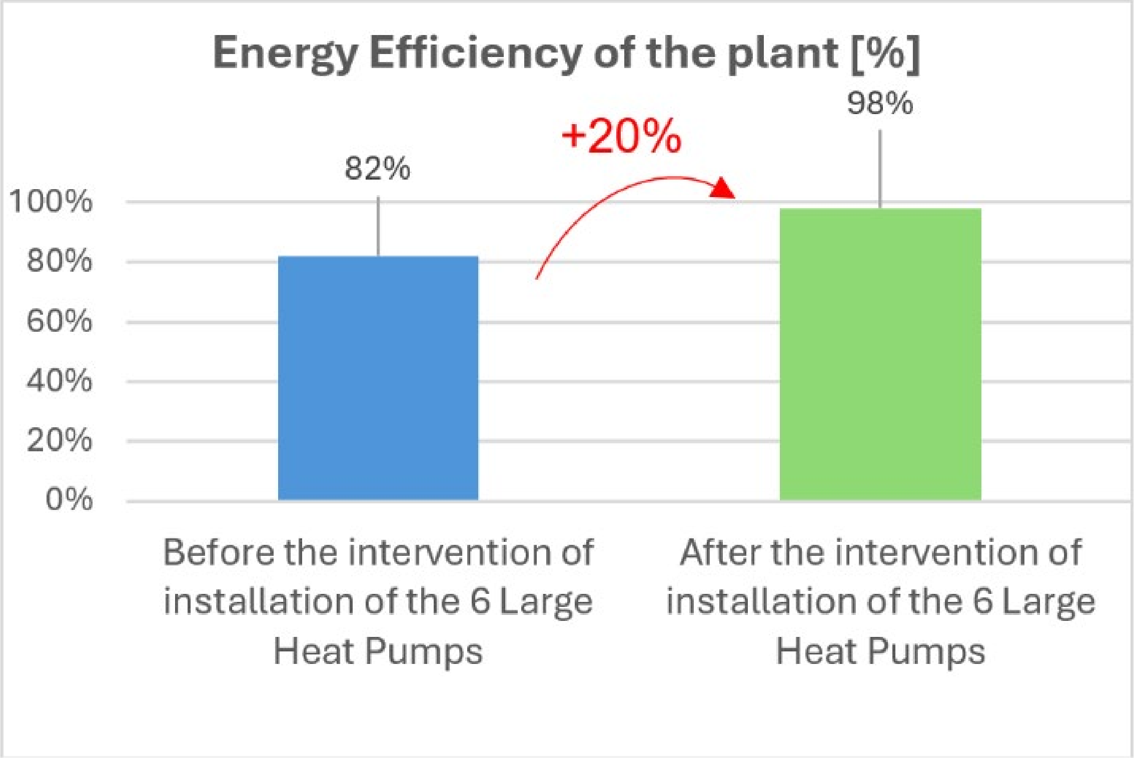

Figure 5: Simplified, non-exhaustive, example of the main results obtained, in terms of energy efficiency, in the Brescia (Italy) waste-to-energy plant, thanks to the introduction of 9 Large Heat Pumps to recover the heat from the flue gases, without increasing the combustion source.

This optimization is a best-in-class example of advanced energy recovery technologies and is fully aligned with A2A Group’s strategic focus on environmental sustainability and circular economy practices.

The Brescia (Italy) Waste-to-Energy plant, where this upgrade was implemented, is owned by A2A Ambiente, part of the A2A Group, an Italian leading Energy Utility Company. This initiative demonstrates A2A Ambiente continued commitment to innovation and leadership in sustainable waste management and energy production.
In addition, stack emissions have been reduced by an average of -40%, further emphasizing the environmental benefits of the intervention. This reduction is due to both the improved thermal efficiency and the lower flue gas temperature resulting from the condensation process, which contributes to reduced pollutant formation and enhanced control over emissions.

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Heat Pumping Technologies
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A HEAT PUMP CENTER PRODUCT

National Market

Switzerland: Heat Pump Market Report

DOI:10.23697/c00r-em19

Stephan Renz, Pierre-Guillaume Christe, Elena-Lavinia Niederhäuser, Switzerland

After a peak of 43,150 heat pumps sold in 2023, sales dropped to around 30,000 units in 2024 and 2025. Switzerland has established comprehensive legislation to achieve net-zero GHG emissions in energy supply by 2050, which enjoys substantial support by the public. However, to meet these goals, significantly more heat pumps must be installed than is currently the case. To achieve these goals, heat pump sales must nearly double. This applies in particular to older buildings constructed before 2000.

Introduction

Heat pumps play an important role in Switzerland's energy system. Switzerland has no fossil fuel resources and starts in the 1920s to develop its hydropower capacity. Heat pumps were therefore an ideal solution for heat generation during times of energy crises. Substantial growth in the building sector began in the 1990s and reached a record high in 2023. The development of the mass market was supported by early quality assurance measures and government subsidies. Heat pumps are now installed almost exclusively in new buildings.

Switzerland in a nutshell

Population 9 million, GDP 900 billion EUR, Area 41’285 km2, highest point “Dufourspitze” (4634 meters ASL), lowest point Brissago (193 meters ASL); Heating degree days (HDD) between 1994 HDD (Lugano 275 m ASL) – 5054 HDD (Davos 1560 m ASL) – 9299 HDD (Jungfrau Joch 3469 m ASL).
Heat pumps installed: In 2024, a total of 469’815 heat pumps were installed, and 21% of the existing buildings were equipped with a heat pump. The target is 1.5 million heat pumps by 2050 [1].

Energy consumption in Switzerland

Final total energy consumption in Switzerland in 2024 amounted to 776,220 terajoules (TJ). The 5+-year comparison (2019 vs. 2024) shows a 7.2% decrease in Switzerland’s total energy consumption, corresponding to 61 TJ. The decline was mainly caused by reduced use of petroleum products (-12.8%) and natural gas (-17.2%). The climatic differences between 2019 and 2024 (calculated using the heating degree days [HDD]) indicate a 6.7% reduction in heating demand. In summary, the climate-adjusted consumption of fossil fuels has fallen by approximately 15%. Electricity consumption increased only slightly, by 1’100 TJ or 0.5%, during this period. For several years now, energy consumption in Switzerland has been decoupled from population and economic growth due to increasingly rational energy use.

Climate change in Switzerland

The temperature in Switzerland has risen sharply since measurements began. The current climate mean is already 3.0 °C above the pre-industrial average of 1871-1900 (as of 2026).

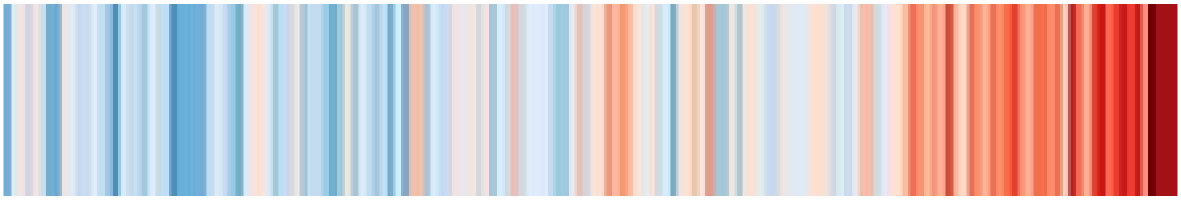

Figure 1: Temperatures in Switzerland since 1864. Every year is shown in a different color. Years with red color-coding are warmer, and those with blue are cooler than the mean of 1961–1990 [1].

Drivers and Policies

The key basis of Swiss energy policy is the article on energy [2] enshrined in the Federal Constitution since 1990. The Energy Act, the CO2 Act, the Climate and Innovation Act, and the Electricity Supply Act all build on this article and together form the body of legislation on which Switzerland's sustainable and modern energy policy is based.

In 2017, the Swiss public voted in favor of the revised Energy Act [3], [4]. This was the first step in implementing the 2050 Energy Strategy. The act bans the construction of new nuclear power plants, strengthens energy efficiency requirements, and significantly expands federal support for renewable energy, while maintaining strong cantonal responsibility for building energy use. The act strongly favors the electrification of heating and the replacement of fossil fuel systems.

At the end of 2020, the SFOE published its Energy Perspectives 2050+ [5]. This document further develops the 2050 Energy Strategy by identifying technological paths across a series of scenarios that outline the objectives of both energy policy (a secure, largely renewable energy supply by 2050) and climate policy (net zero emissions by 2050).

Laws are periodically adapted to address new boundary conditions or strengthened to reflect recent developments. New or revised acts are subject to an optional referendum and can be rejected by the public, as happened to the revised CO2 Act, which was rejected in June 2021. On March 15, 2024, an amended version of the revised CO2 Act was passed by parliament and brought into force [6].

Based on an initiative submitted in November 2019, the Federal Council adopted a Federal Act on Climate Protection Goals, Innovation and Strengthening Energy Security [7]. After the act passed the parliament in June 2022, opponents successfully filed a referendum against it. But in June 2023, the Swiss public voted (with 59.1%) in favor of this new Federal Act, which creates a framework for Swiss climate policy and sets interim targets for reducing greenhouse gas (GHG) emissions by 2050.

In June 2021, the Federal Council adopted the Federal Act on a Secure Electricity Supply from Renewable Energy Sources. The act is based on the conclusions of Energy Perspectives 2050+ and results from a revision of the Energy Act and Electricity Supply Act. The key aim is to strengthen Switzerland’s security of supply, particularly in the winter months, by expanding domestic renewable electricity production and setting binding expansion targets and energy consumption reduction targets. The bill was passed by parliament in September 2023. Because a referendum was successfully filed against it, a public vote was held in June 2024. The revision of the acts was accepted with 68.7% approval, and the act came into force in January 2025. [8]

In summary, it can be concluded that Swiss voters strongly support the federal government’s energy and climate policy. Despite this robust legal framework and the deployment of multiple incentive schemes and support mechanisms, the effective pace of transformation of the Swiss energy system remains a key challenge.

Energy-legislation at cantonal level

The cantons are responsible for building legislation. To harmonize energy legislation across Switzerland's 26 cantons, their energy ministers drafted a model bill in 2014 [9]. In this law, heat pumps are a preferred solution for heat generation. The cantonal parliaments may amend the model bill, and citizens have the right to call for a referendum. By 2025, all but one canton have implemented the law with their own amendments. In the meantime, the energy ministers have passed the 2025 bill, and the cantons are beginning to implement it.

Incentives

Each canton sets its own subsidy amounts for energy efficiency measures in the building sector. The amount of the subsidies varies widely. Some cantons provide a subsidy of CHF 2,000 for heat pumps, while others offer CHF 10,500 for 10 kW air-to-water heat pumps and CHF 30,000 for ground-source heat pumps. With the Climate and Innovation Act, additional incentives have been introduced for renewable heating systems with a minimum power of 70 kW. It also contains measures for the integration of district heating networks and seasonal thermal energy storage [10].

Market overview – until 2017

The heat pump market in Switzerland dates back to 1878, when the world's first commercially used vapor recompression plant was installed at the saltworks at Bex. In the years that followed, heat pumps were primarily developed and used in industry and for refrigeration applications. A first peak occurred during World War II, when numerous large-scale systems were installed for building heating. Until the 1970s, fossil fuels were the primary energy source. The oil crises of 1973 and 1978 triggered the construction of several large-scale heat pump systems integrated with district heating networks.

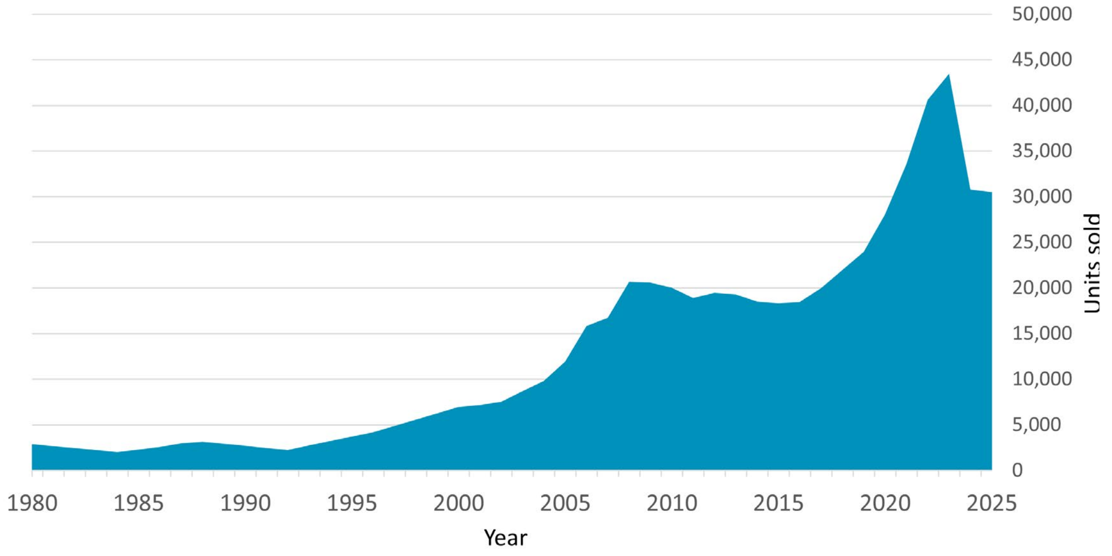

Figure 2. Sales figures for heat pumps per year in the Swiss market [11]

Sales of smaller heat pumps for central water heating systems in single-family homes and larger residential buildings started only in 1980s (Figure 2). Until mid-1990s, around 2000 - 3000 heat pumps were sold each year. Establishing the Swiss Association for the Promotion of Heat Pumps (FWS) in 1993 accelerated the sales. Its tasks include the provision of information and advice, education and training, advocacy and quality assurance [12]. Sales rose rapidly in the mid-1990s and reached a first peak in 2007 with 20,670 units. Until 2017, sales figures remained flat at just under 20,000 units per year.

Development 2017 - 2025

From 2017 onward, the number rose steadily until 2023, when a preliminary peak of 43,490 heat pumps was reached. The decline in heat pump sales observed in 2024 applies to units with a capacity of up to 20 kW. Higher electricity prices starting in 2023 and the very high demand for heat pumps from 2021 to 2023 have led to negative effects in the heat pump market (e.g. price surcharges, delivery problems, and a smaller price difference between heating systems in terms of annual energy costs). Issues such as the mandatory use of natural refrigerants, noise protection regulations, historic preservation requirements, and permitting procedures are having an additional negative impact on heat pump sales.

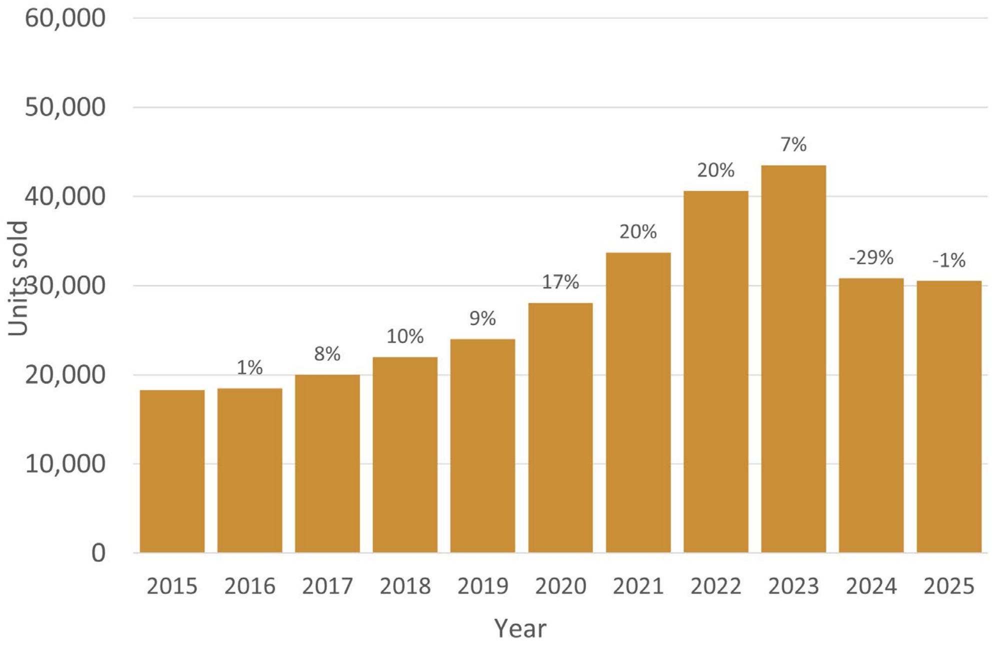

Figure 3: Annual heat pump sales, 2015–2025 [11].

The statistics are based on self-reported data from manufacturers/suppliers. They do not include hot water heat pumps (7903 units sold in 2023), large heat pumps, e.g. in district heating applications or custom-made products for the industry.

Power of the heat pump sold

Further analysis of sales figures shows that 85% of the units sold have an output of less than 20 kW and 97% are below 50 kW (Figure 4).

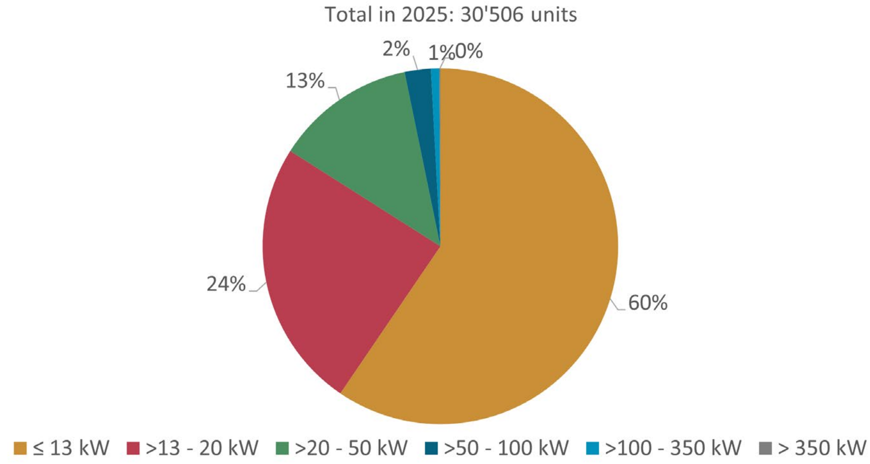

Figure 4: Heat pump sales by power in kW in the Swiss market for 2025 [11].

In recent years, however, there has been a growing trend toward installing or planning large-scale heat pump systems to supply district heating networks or new neighborhoods. Some of these projects involve low-temperature networks (Zurich) or are implemented as Positive Energy Districts (Cham). This goes hand in hand with the ambitious goals of major Swiss cities to become "climate-neutral" (Basel: 2037, Zurich:2040, Bern 2045).

Air-to-water heat pumps are the most popular (72%), followed by ground source heat pumps (27%). Air-to-air heat pumps are rarely installed in Switzerland (Figure 5).

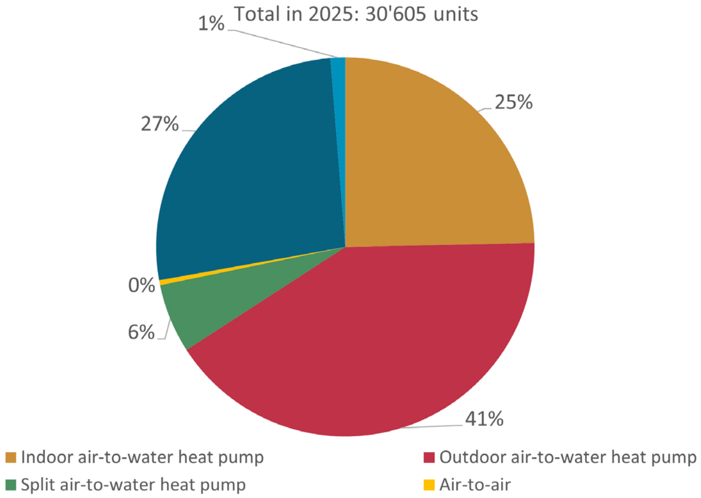

Figure 5. Percentage distribution of heat pump sales by energy source in 2025, [11]

Heat pumps account for a very high proportion in the number of heating systems sold annually in Switzerland. In 2025, the figure was 59% (Figure 6).

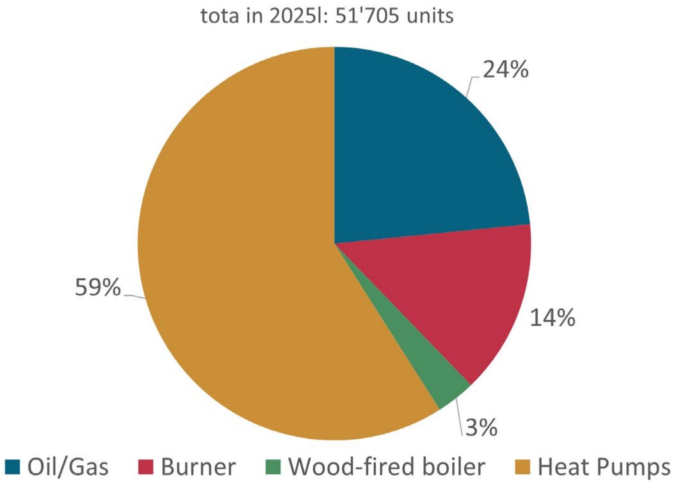

Figure 6. Sales figures for heat generation units and oil/gas burners in the Swiss market for 2025 [11].

In buildings constructed after 2011, oil-fired heating systems are rarely installed, and gas-fired systems are becoming increasingly rare. The heating systems are sustainable, with heat pumps accounting for the majority. The older the buildings are, the fewer heat pumps are installed (Figure 7).

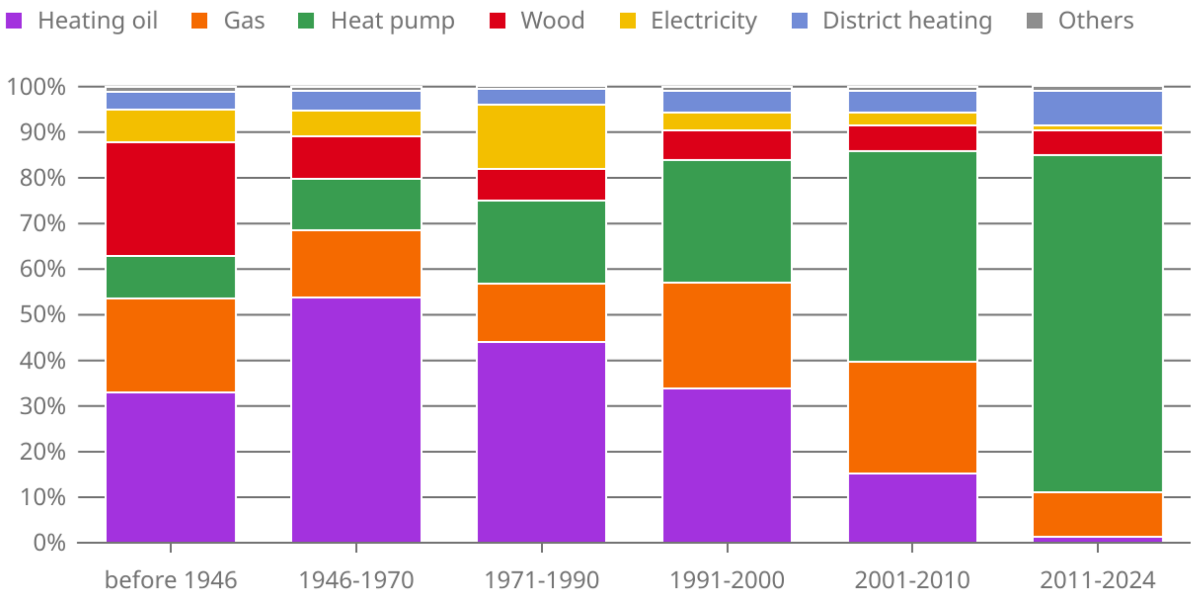

Figure 7: Residential buildings by main heating energy source and period of construction (2024) [13].

Conclusions

Fossil fuels have long influenced the development of the Swiss heat pump market, albeit through different mechanisms over time: historically through supply bottlenecks (physical constraints and price volatility), and today through the need to decarbonize the energy system. While energy and environmental policies, supported by incentive schemes, clearly favor the deployment of heat pumps, current sales volumes remain insufficient to meet long-term climate and energy objectives – particularly in the existing building stock, where technical and economic barriers are greatest. Moreover, market statistics only partially capture recent dynamics, as large heat pumps for district heating and industrial applications are typically excluded. In these segments, growth is increasingly reflected in installed capacity rather than unit numbers.

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