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Heat Pumping Technologies
MAGAZINE
Natural Refrigerants in Heat Pumps: Pushing the Boundaries of Sustainability

Vol.43 No. 1/2025
A HEAT PUMP CENTER PRODUCT

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In this Issue

Welcome to Issue 1/2025 of Heat Pumping Technologies Magazine! We are excited to present the very first edition of *Heat Pumping Technologies Magazine* for 2025, dedicated to a crucial and timely theme: **"Natural Refrigerants in Heat Pumps: Pushing the Boundaries of Sustainability."**

As the global urgency for sustainable solutions accelerates, the heat pump sector is evolving rapidly to meet the challenge. Natural refrigerants, including carbon dioxide (CO_2), ammonia, hydrocarbons, and water, are gaining significant momentum due to their low global warming potential (GWP) and minimal environmental footprint. In this issue, we explore how these environmentally friendly alternatives are redefining heat pump technologies, driving innovation, and shaping the future of sustainable heating and cooling.

We begin with the **Foreword**, titled **"Natural Refrigerants in Heat Pumps: Pushing the Boundaries of Sustainability,"** setting the tone for an in-depth exploration of how natural refrigerants are leading a transformation in the industry.

Our **Column**, **"From Legacy to Leadership: District Heating in Eastern Europe as a Platform for Large-Scale Heat Pumps,"** examines how district heating systems are becoming fertile ground for large-scale sustainable heat pump integration.

The **Topical Section** showcases a series of articles highlighting cutting-edge research, technological breakthroughs, practical case studies, and forward-looking policy frameworks aimed at accelerating the adoption of natural refrigerants:

- **Beyond Climate Change: Sustainability Assessment of Heat Pumps and Refrigerants**
- **Oil Meets Cool: Inside the World of Lubricant-Refrigerant Properties**
- **Domestic Heat Pumps Using Hydrocarbons: Current Status and Market Overview in Europe**
- **Review of Heating and Cooling Applications Where Hydrocarbons Have Been Introduced as Refrigerants and Future Perspectives of Their Use**
- **Modeling Leaks of Flammable Refrigerants**

In the **National Market Section**, we turn our focus to the Netherlands with an exclusive **"Heat Pump Market Report,"** offering valuable insights into one of Europe's most dynamic markets for sustainable heating and cooling solutions.

This debut issue captures the drive, ambition, and innovation shaping the next generation of heat pumps. We invite you to dive in and discover how natural refrigerants are pushing the boundaries of what is possible for a more sustainable world.

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

Natural Refrigerants in Heat Pumps: Pushing the Boundaries of Sustainability

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

In Europe, the F-gas regulation from last year has increased the rate of the phase-down of synthetic refrigerants. By 2050, HFCs will no longer be allowed to be put on the market. The HFOs are excluded from this phase-out, but will be hit by the prohibition to market products with a nominal capacity of less than 12 kW, using any type of F-gases (unless required for safety reasons). In the rest of the world, the Kigali amendment to the Montreal Protocol prescribes a (slower) phase-down of the use of F-gases. In parallel, there is a growing concern about the release of PFAS, also known as "forever chemicals". Almost all synthetic refrigerants belong to the PFAS group (according to the OECD definition). In the EU, there is a proposal to ban the use of all PFAS substances. Restrictions of these substances is also discussed or implemented in other parts of the world, e.g., in some states in the US. As the refrigerants constitute about 60% of all released PFAS, it can be expected that these restrictions will include most of the synthetic refrigerants we use today.

As a result of the implemented and expected restrictions on synthetic refrigerants, most manufacturers in Europe are already introducing products using natural refrigerants. As Europe is an important market also for companies outside of the EU, producers from other countries are developing products with natural refrigerants as well. At Chillventa last year, there were about 15 Chinese companies displaying heat pumps with hydrocarbons! As shown in a recent Technical Brief by the IIR [1], the sales of hydrocarbon heat pumps, as well as the number of models on the European market, have increased considerably over the last few years.

For domestic heat pumps, the most common natural refrigerant is propane, R290. As this is a highly flammable substance, it is important to ensure that the products and installations are safe. The standard IEC/EN/UL 60335-2-40 describes how safe products with flammable refrigerants can be designed, also for installation indoors. In the EU, an updated version of the EN378 on safety and environmental requirements for refrigeration systems and heat pumps is expected to be launched soon. In general, safety can be increased, e.g., by reduced charge, increased tightness, tight enclosures ventilated to the ambient, sensors to switch off the systems in case of a leak, etc.

Research related to these topics is ongoing at many universities in Europe as well as in the US, Japan, and China. Part of this work is done within the IEA HPT Annex 64. The work on charge reduction has demonstrated, by Fraunhofer ISE [3] and independently by KTH [4] [5], that it is possible to build a heat pump with a capacity of 12 kW using only 120 g of hydrocarbon. To reach a low specific charge, it is necessary to consider all the components in the system. We can therefore expect in the near future to see enhanced designs of heat exchangers, as well as new types of compressors, with low charge of oil (or oil-free), and small internal volume.

For larger systems like heat pumps for district heating, we already see a growing market for CO_2 heat pumps. But hydrocarbons are also being introduced in very large systems, both for district heating (50 MW) [5] and for industrial applications [6] [7]. And, we should not forget that ammonia has been the standard solution in industrial applications of heat pumping technologies for more than 100 years.

Every year, there are several fires caused by gas heaters and the gas networks in the built environment. Exchanging these heaters for heat pumps with natural refrigerants, even if they are flammable, would probably be a much safer alternative. And much better for the environment!

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Column

From Legacy to Leadership: District Heating in Eastern Europe as a Platform for Large-Scale Heat Pumps

By Tomas Caha, Consulting Engineer, Exergie Czech Republic

What if Eastern Europe's energy legacy became its greatest asset in the climate transition?

Eastern Europe's district heating systems, once considered relics of centralized planning, now represent a strategic opportunity in the clean energy transition. These extensive networks are uniquely positioned to accelerate the deployment of large-scale heat pumps, transforming a perceived challenge into a competitive advantage.

While Western European countries like Germany struggle with limited district heating coverage (approximately 11%), Eastern European cities enjoy remarkably high penetration rates. In urban centers such as Bucharest, Warsaw, Sofia, and Prague, these networks satisfy 40–70% of residential heating demands. Despite aging infrastructure and a legacy reliance on fossil fuels, they provide a ready-made foundation for cost-effective urban heating decarbonization.

A common criticism concerns high operating temperatures (60–120°C), which often exceed both practical requirements and conventional heat pump capabilities. Yet this challenge is not unique to Eastern Europe; similar constraints exist in Germany, the Netherlands, or Austria. Across the EU, solutions are already being implemented: staged temperature reduction, thermal storage, and advanced high-temperature heat pumps are proving effective in overcoming this barrier.

Gas Legacy and the Case for Heat Electrification

The region's historical gasification presents a significant hurdle. Legacy infrastructure and subsidized pricing schemes have kept gas artificially affordable, delaying investments in clean heating. However, the inclusion of the building sector in the EU ETS II could dramatically shift this dynamic. Meaningful carbon pricing would substantially improve the economics of renewable heat, particularly for large-scale heat pump deployment.

Beyond emissions reduction, electrifying heat unlocks broader energy system benefits. Heat pumps bridge the heat and power sectors, enabling load flexibility, grid support, and efficient use of surplus renewable electricity. As variable renewables grow and traditional base-load generation declines, this flexibility becomes increasingly valuable, turning heat electrification into both an environmental and strategic asset.

Call to Action: Aligning Policy, (Political) Capital, and Courage

Cities like Zagreb, Bratislava, and Budapest are ideally positioned for centralized heat pump deployment, provided that supportive policy frameworks are in place. Their advantages include municipal ownership of district heating networks, high urban density, and broad public acceptance of centralized heat supply. These conditions simplify transactions and enable integrated urban energy planning.

However, this opportunity also requires political leadership. City governments must act now, even if the full benefits of transition will materialize beyond the next election cycle. Long-term vision and institutional continuity are key to delivering energy systems that serve both today's needs and those of future generations.

Fortunately, European policy is moving in the same direction. EU legislation provides critical momentum through multiple instruments: the Renewable Energy Directive (RED III) mandates increased renewable heat adoption; the Energy Efficiency Directive (EED) defines efficient district heating criteria; and the Energy Performance of Buildings Directive (EPBD) drives demand for zero-emission buildings. National frameworks that align with these instruments will be essential for unlocking investment potential.

Eastern Europe possesses a unique combination of structural assets despite technical constraints. With appropriate policy support, including long-term price signals, access to EU investment tools, and regulatory clarity, the region could emerge as a heat transition leader. This is not just a technical upgrade; it is a strategic opportunity to build future-proof, resilient cities. Eastern Europe doesn't need to catch up. It can lead.

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Topical Article

Beyond Climate Change: Sustainability Assessment of Heat Pumps and Refrigerants

DOI: 10.23697/byeq-t463

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Replacing boilers with heat pumps significantly reduces greenhouse gas (GHG) emissions, thus rendering them a vital component for the energy transition. The F-Gas and REACH regulations further support GHG reductions by limiting high global warming potential refrigerants. However, heat pumps may shift burdens to other environmental categories beyond climate change, risking overall sustainability in the long term. This study employs a life cycle assessment to evaluate the environmental performance of a heat pump using seven different refrigerants. The findings show that R290 and R717 achieve higher seasonal coefficients of performance (SCOP 3.83-3.88) than, e.g., R1234yf (3.36), reducing indirect emissions in 9 analyzed impact categories by 10-16% through lower electricity demand. As a next step, the integration of circular strategies and the compressor's lubricant into the assessment is recommended due to its interaction with efficiency in the compressor, its impact on the compressor envelope, and heat pump life-time.

Introduction

The transition from boilers to heat pumps in residential heating is critical for reducing greenhouse gas (GHG) emissions and advancing energy transition. However, despite their potential, heat pump adoption in Europe, particularly Germany, faces declining sales [1]. Heat pumps produce both direct and indirect emissions, influenced by, e.g., refrigerant choice, leakage rates, grid electricity CO_2 intensity, and system efficiency. Existing studies focus either on climate change mitigation via refrigerant choice or on broader environmental impacts with fixed setups, often neglecting burden-shifting to other impact categories. This study summarizes the findings from a previously published journal article in which a comprehensive life cycle assessment (LCA) of heat pumps and refrigerants was conducted, encompassing 15 environmental categories beyond climate change [2]. The study incorporates a refrigerant-dependent heat pump model and a building performance simulation model, which are employed to account for refrigerant impacts, operational efficiency, and building-specific heating demands.

Environmental Performance of Heat Pumps and Refrigerants

This study evaluates the environmental impacts of an air-to-water heat pump operating in a German single-family house over a 20-year period, using refrigerant R410A in the baseline scenario. The analysis follows the cradle-to-gate setup with fixed end-of-life rates in Figure 1 (left) and considers heat pump production (Figure 1, right) and operation, refrigerant production, refrigerant leakage, and upstream processes, excluding distribution systems and building envelopes. The assessment of environmental impacts is aligned with the International Life Cycle Data System (ILCD) guidelines [3].

Sixteen impact categories were calculated from which nine are presented in this study, with a particular emphasis on climate change, and using ecoinvent [4] datasets for material and energy flows. Furthermore, a comparative analysis of six alternative refrigerants (i.e., R32, R1234yf, R290, R1270, R600a, R717) in 9 out of 16 impact categories is conducted to assess their life cycle impacts, including production, operation, and constant end-of-life factors. These impacts are normalized and weighted in accordance with ILCD recommendations to be comparable with a standard gas condensing boiler.

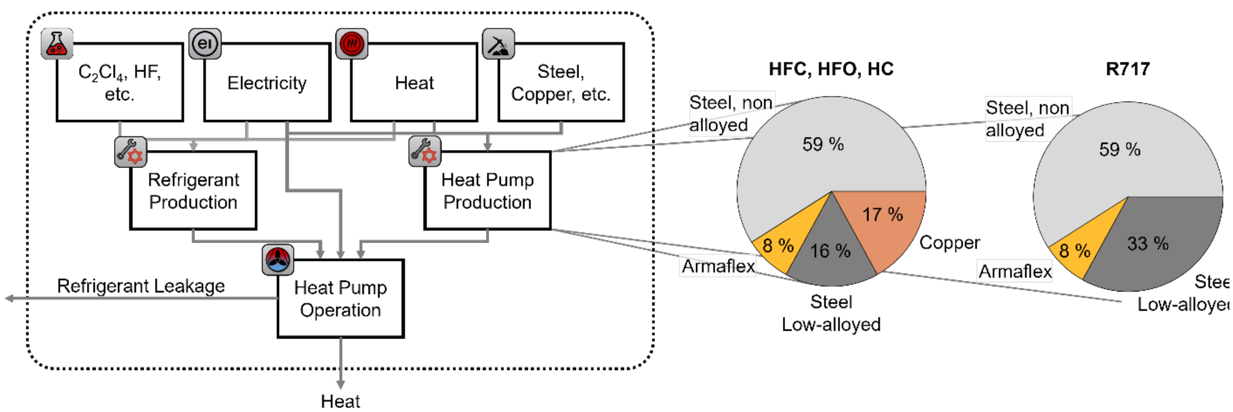

Figure 1: Process models and their interconnection during a life-cycle (left), providing heat using two different heat pump production routes based on the deployed refrigerant (right).

The life cycle inventory includes a sound data basis and modelling approaches. A detailed description of the method is presented in Vering *et al.* 2025 [2], in which the modelling of refrigerant production, including chemical reactions and leakage assumptions, is explained. Heat pump manufacturing is based on a 10 kW brine-to-water system, with material compositions (see Figure 1, right) scaled per nominal heating power and average specific weights of 18 kg/kW applied across refrigerants. Leakage rates of 5% annually and 30% at end-of-life are assumed to calculate refrigerant losses and environmental impacts. The heat demand simulation employs the TEASER framework, utilising weather data for Erfurt and a modelled three-story house with 280 m^2 living area, yielding an annual heat demand of 82 MWh and a peak load of 22.5 kW, which is provided at the national grid mix in Germany of 2020.

Hundreds of refrigerants are available for heat pumps, each with unique advantages and disadvantages. The synthetic refrigerant R410A is the industry standard due to its non-flammability and hazard-free operation, despite its environmental drawbacks due to high global warming potential (GWP). Conversely, alternatives such as propane (R290) and ammonia (R717) offer higher efficiencies but pose safety challenges due to flammability or toxicity, requiring stricter standards [5]. Additionally, synthetic refrigerants such as R410A, R32, and R1234yf have been found to produce PFAS [6], raising concerns regarding pollution and potential bans, which could potentially disrupt heat pump adoption.

This study examines seven refrigerants (see Figure 2), including R410A, R32, R1234yf, R290, R1270, R600a, and R717, utilising a fluid-dependent heat pump model to calculate seasonal performance coefficients (SCOPs) and environmental impacts compared to a gas condensing boiler. The findings reveal that R290 and R717 achieve higher SCOPs (3.83 and 3.88, respectively) compared to R1234yf (3.36), thereby reducing electricity demand and climate impacts by 10–16%. Switching to natural refrigerants like R717 also reduces ozone depletion and production-related impacts by eliminating chlorine- or fluorine-containing substances. Using stainless steel instead of copper, required for R717, further decreases production impacts but may increase costs.

Despite its reduced environmental efficiency, R410A serves as a baseline for assessing heat pump impacts under different aspects. This underscores the significance of refrigerant selection in optimizing the sustainability of heat pumps while balancing safety and efficiency.

The distinction between direct and indirect emissions is central to the environmental assessment of heat pumps. Direct emissions are caused by refrigerant leakages during production, operation, or disposal. Due to the high GWP of synthetic refrigerants such as R410A, these can make a noticeable contribution to climate change. Indirect emissions, on the other hand, result primarily from electricity consumption during operation. Therefore, indirect emissions are strongly influenced by the CO_2 intensity of the electricity mix and the system's efficiency. As part of greenhouse gas accounting (ESG-Reporting), the Greenhouse Gas Protocol distinguishes between three scopes:

- Scope 1 includes direct emissions from own sources, e.g., refrigerant leakages.
- Scope 2 includes indirect emissions from purchased energy, such as electricity consumption during operation.
- Scope 3 takes into account other indirect emissions that occur along the value chain, e.g., production of the heat pump or transport of refrigerants.

Figure 2 shows that only refrigerants with high GWP cause significant Scope 1 emissions due to leakage. Furthermore, it is evident that Scope 2 emissions dominate the environmental impact due to electricity use during operation under German grid mix conditions from 2020. Consequently, the SCOP significantly influences indirect emissions, making R717 – with its superior efficiency – particularly favorable in terms of overall environental performance. Finally, compared to the gas boiler, it is evident that burden-shifting occurs in 6 out of 9 categories. Therefore, the overall sustainability of heat pumps has to be taken into account in the future to reduce the overall environmental impact.

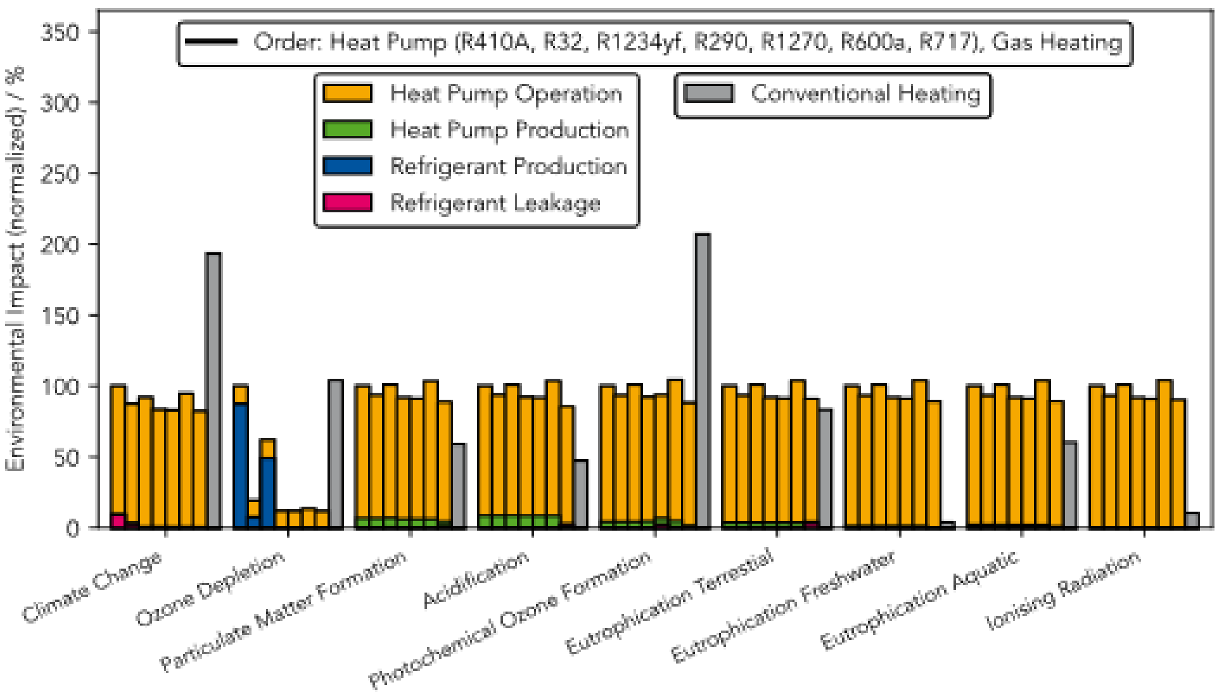

Figure 2. The environmental impacts of a heat pump are shown for each environmental category and each refrigerant (standardised to R410A). The environmental categories are according to the ILCD Recommendation Levels [3].

Limitations

Heat pumps with heating capacities of approximately 25 kW, as examined in this study, commonly utilize positive displacement compressors. These compressors are lubricated, leading to the introduction of lubricants into the heat pump LCA. Common lubricants for heat pumps include mineral oils and synthetic options such as polyalpha-olefins, polyalkylene glycols, and polyol esters. Both can be produced through petrochemical processes, yielding further Scope 3 emissions. Moreover, the choice of lubricant significantly affects both the efficiency and capacity of heat pumps. Higher viscosities result in increased friction losses while minimising losses due to reverse flows. Additionally, lubricant is injected from the compressor into the refrigerant cycle, where it can create a film on all surfaces that may insulate the heat exchangers and decrease their efficiency. Therefore, the selection of lubricant can influence the power consumption of the heat pump and its operational Scope 2 emissions. [7,8,9].

The present study has not addressed the impact of the production, handling during maintenance, efficiency impacts, and end-of-life management of lubricants, yet, which is recommended to get the bigger picture of sustainability assessment. In addition, the introduction of circular strategies compared to constant linear end-of-life strategies could be helpful, further reducing overall emissions compared to the gas condensing boiler [10].

Conclusions

This work presents an insight into an in-depth life cycle assessment of heat pumps and refrigerants compared to gas boilers. Under 2020 grid mix conditions in Germany, greenhouse gas emissions can be significantly reduced when heating a building with a heat pump. However, burden-shifting occurs, meaning that the environmental impact in other categories increases when switching to heat pumps. In this regard, the study now reveals leavers for future development: (1) provision of green electricity, (2) utilizing heat pumps with high efficiencies, and (3) changing to low-GWP refrigerants is key for minimizing environmental impacts. For future work, we recommend including the compressors lubricant and circular strategies into the assessment to get the bigger picture of LCA assessment and finding optimal solutions for refrigerant and oil combinations in heat pumps.

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Topical Article

Domestic Heat Pumps Using Hydrocarbons: Current Status and Market Overview in Europe

DOI: 10.23697/5n82-6f13

Emilio Navarro-Peris (Spain), Daniel Colbourne, United Kingdom, Thore Oltersdorf, Germany, Björn Palm, Sweden and Alberto Coronas, Spain.

Governments are promoting the shift to electrically-driven heat pumps for domestic heating and hot water, while also regulating the use of environmentally-damaging fluids. Natural refrigerants, particularly hydrocarbons (HCs), are gaining attention due to their low toxicity, and excellent thermophysical characteristics, despite being flammable. HCs are seen as sustainable long-term alternatives to synthetic fluids. This article is based on a Technical Brief with the same title published by the International Institute of Refrigeration [1], which explores the current use of HCs in domestic heat pumps, their advantages and limitations compared to other options, and prospects for broader adoption.

Introduction

Global warming and climate change require a phase-out of fossil fuels. The residential sector is particularly important to decarbonise as it is responsible for one-third of all the global warming emissions in Europe. A significant portion of the emissions of this sector comes from heating, which is mainly powered by fossil fuels. In Europe, efforts to reduce emissions include the electrification of these systems, particularly through Domestic Heat Pumps (DHPs), which are seen as the natural alternative.

The EU aims to install a total of 30 million DHPs by 2030. This is part of the broader goal to reduce greenhouse gas emissions by 55% by 2030. The use of DHPs has increased significantly in recent years, with air-to-air and air-to-water models becoming more popular. Despite a decline in global sales in 2023 and 2024, DHP market share is expected to continue to rise if the decarbonization objectives are maintained.

By 2040, DHPs are expected to be the leading heating and cooling technology worldwide. However, there are challenges regarding the refrigerants used in DHPs, as many are harmful to the environment. Low Global Warming Potential (GWP) refrigerants are required to meet the Kigali Amendment and European F-gas regulations. In Europe, the F-gas regulation will forbid installations of heat pumps with any F-gases in small systems (<12 kW) from 2035, unless required by safety concerns. Among the options, HCs are promising if their flammability is managed properly.

This article summarizes the overview of the current possibilities of using HC refrigerants for DHPs supplied in the Technical Brief [1]. First, a motivation for the selection of HCs as the most suitable refrigerant for this application is given, followed by the main characteristics of DHPs when using HCs, including their charge limits. Next, an overview of the commercially available HPs using HCs and their possibilities in the framework of the EU F-Gas regulation 2024/573 is presented (EU Parliament and Council, 2024). It concludes with considerations of possible technological evolutions that could extend the application range of HCs in HPs.

Why HCs?

HCs, have excellent thermodynamic properties compared to other refrigerants; they have a high isentropic COP, work at low pressure ratios, which benefits the compressor efficiency, have a low discharge temperature which is translated in a wider operation map and have a high heat transfer coefficient which allows a competitive cost of the heat exchangers. From the environmental point of view, other than their negligible GWP, since they are naturally occurring fluids whose interactions in the environment are very well known, thus no unexpected effects can be expected from their widespread use.

Regarding flammability, new standards have been approved in the last years, such as EN IEC 60335-2-40, in order to ensure their safe application. EN 378 is also currently being revised. These standards offer a variety of flammability risk mitigation concepts (RMCs) that can be applied to DHPs, according to system type, installation location, refrigerant charge, etc. Essentially, these RMCs include approaches to reduce leakage, avoidance of potential sources of ignition, airflow to disperse leaks, and provision of user and operator information.

Perspective of Hcs as Refrigerants

Heat Pumps Currently Available

Regarding R290 DHPs, as of 2022, HP Keymark database included about 420 products using R290 refrigerant. DHPs can be categorised by their source and sink mediums: air to water (ATW), liquid to water (LTW), and air to air (ATA).

ATW systems: Typically used for space heating and domestic hot water (DHW), these systems include outdoor monoblock units with almost no restrictions when they are placed outdoors. Split systems may also be used, but can be limited by refrigerant charge and capacity depending on design. They have become a key alternative to gas boilers, gaining significant market share due to their simplicity. In the HP Keymark database of 2022, 203 R290 ATW DHPs were listed, compared to 1,095 HFC ATW products. Looking at Figure 1, ATW performance data shows that many R290 /models outperform R410A and R32 models in Seasonal Coefficient of Performance (SCOP). Additionally, the refrigerant charge tends to increase with Nominal Heating Capacity (NHC), with R290 models offering high capacities with no more than 1 kg of refrigerant. Specific charge for the best models is around 50 g/kW.

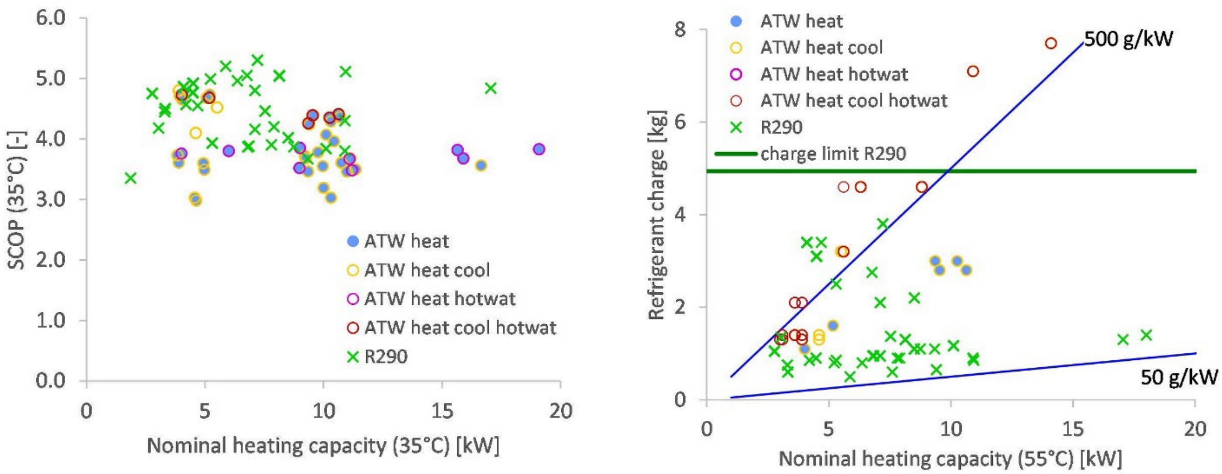


Figure 1. Left) SCOP as a function of nominal capacity for ATW HPs depending on the used refrigerant. Right) Refrigerant charge as a function of the nominal capacity for ATW HPs depending on the used refrigerant [1]

LTW systems: These heat pumps are less common than ATA or ATW models. In the HP Keymark database [8], 127 LTW models use R290, compared to 408 HFC LTW products. Figure 2 shows that R290 HP models have a higher SCOP than models with other refrigerants, independently of (NHC). Refrigerant charges for LTW are typically lower than ATW units; for this typology, it is common to find specific charges of 25 g/kW.

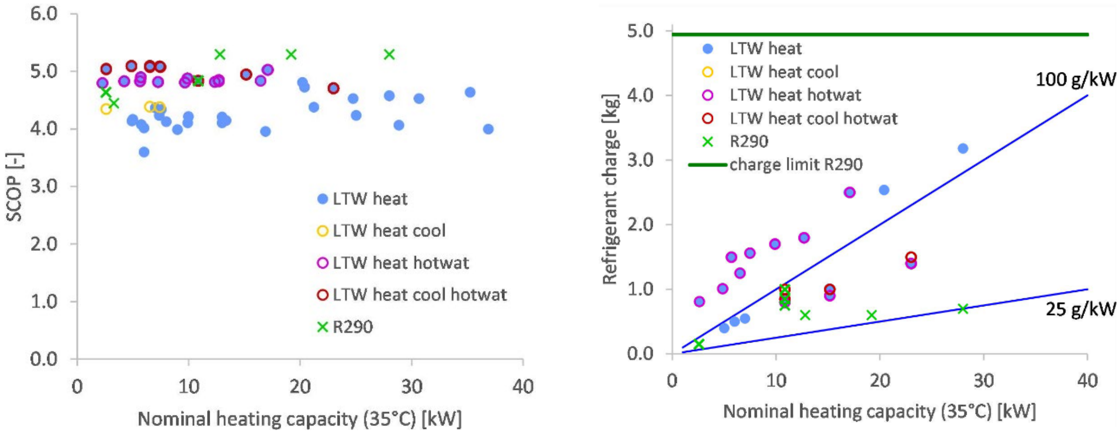


Figure 2. Left) SCOP is a function of nominal capacity for LTW HPs depending on the used refrigerant. Right) Refrigerant charge as a function of the nominal capacity for LTW HPs, depending on the used refrigerant [1]

ATA systems: These are dominant in the market nowadays. Their typical capacities are under 12 kW and are primarily dominated by R410A and R32. In fact, a recent study [2] reviewed over 2,500 reversible ATA heat pumps, showing that less than 1% used R290. The study also presents an analysis of charge limits for R290 depending on the capacity (see Figure 3) based on the limits imposed by EN IEC 60335-2-40:2024 and performing quite conservative assumptions arrives to the conclusion that the use of HCs – particularly R290 and R1270 – is broadly feasible in high- efficiency reversible models for NCCs up to 12 kW.

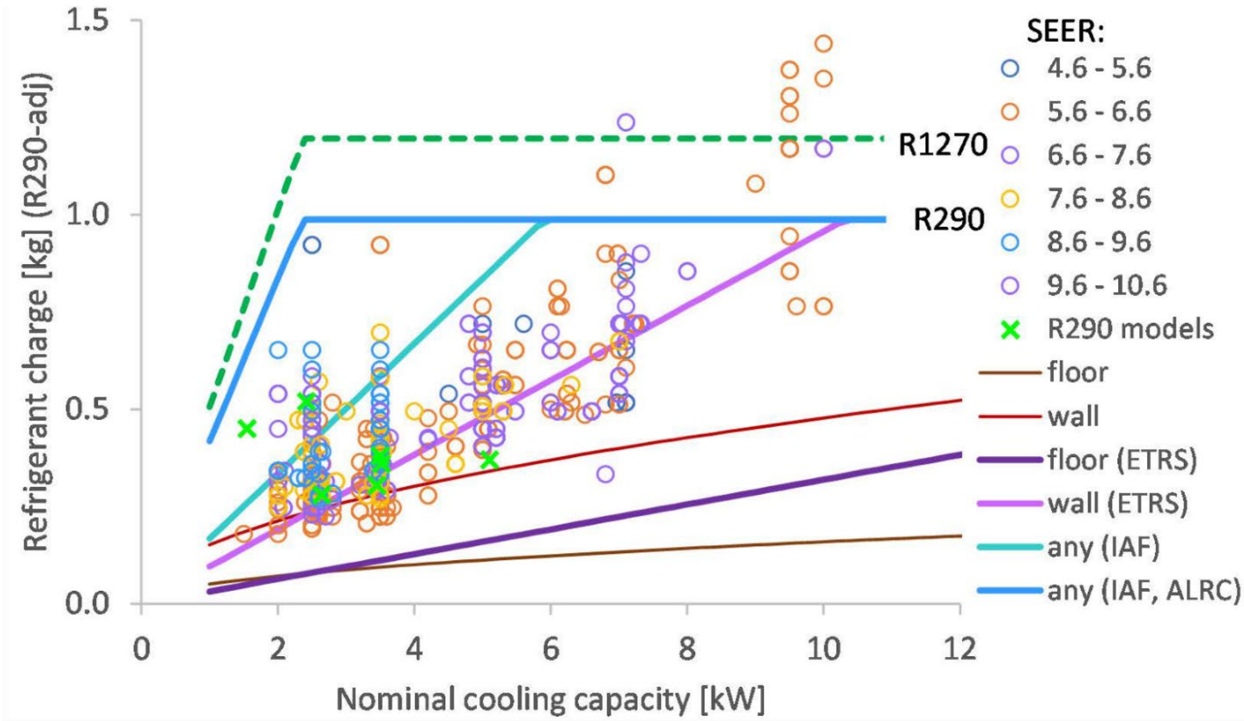


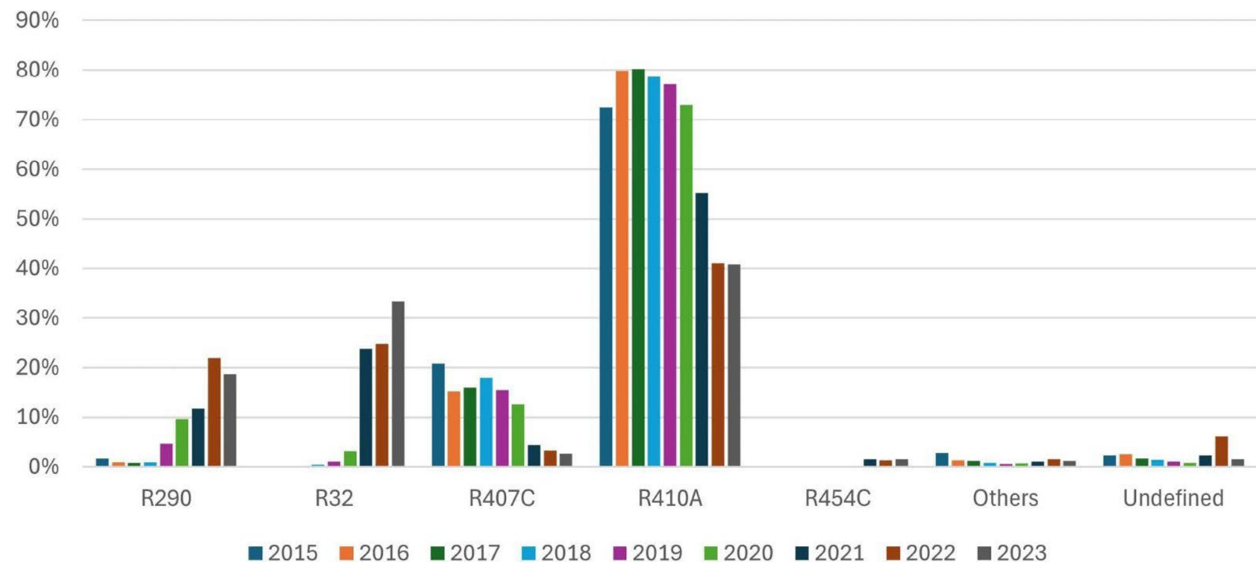
Figure 3. Allowable charge of R290 if different safety precautions are followed, superimposed with charge-adjusted catalogue data [1]

Regarding the price of the units, large-scale cost analyses presented in [2] showed that using DHP based on R290 is generally neutral compared to other refrigerants, with advantages in terms of reduced material mass, manufacturing emissions associated to the components but also to the refrigerant itself, and charge amount and cost. This statement is also verified by performing a market study through pages like Idealo. In markets outside Europe, such as China and India, R290-based systems are being introduced more widely, with several large manufacturers developing R290 reversible AC/HPs.

Market Penetration

In the previous subsection, the number of HP models available was analysed; now, the sales of heat pumps depending on the refrigerant is going to be studied to measure the penetration of HCs based on limited data from the German market according to the BEG funding scheme (Bundesförderung energieeffiziente Gebäude)[1].

From 2015 to 2023, the share of R290 refrigerants in subsidized HPs grew to about 20% by 2022. This share was even higher for monoblock ATW systems. However, in 2023, R290's share dropped, while R32-equipped systems continued to grow. One reason for these dynamics could be found in the different shares of R290 depending on the HP type, which was not reflected in that classification, see Figure 4.



Annual change	R407C	R410A	R290	R32	Comment
2017-2018	+1.8%	-1.7%	+0.1%	+0.3%	
2018-2019	-2.3%	-1.4%	+3.6%	+0.8%	Intro of several new R290 DHPs on the (subsidized) market
2019-2020	-2.9%	-4.3%	+5.2%	+2.1%	Intro of several new R290 and R32 DHPs on the (subsidized) market
2020-2021	-8.3%	-17.7%	+2.1%	+20.6%	New funding scheme in 2021 (BEG) incl. ATA DHPs
2021-2022	-1.1%	-14.1%	+10.1%	+1.0%	Intro of new R290 HPs, new funding scheme in 2021 (BEG) incl. ATA DHPs
2022-2023	-0.5%	-0.3%	-3.1%	+8.6%	Simplified access of (multi-)split DHPs (mainly R32) to subsidization; supply issues for R290 DHPs

Figure 4. Evolution of the dynamics of shares of refrigerants wanted by house owners in Germany as well as annual changes and reasons for shifts between refrigerants [1]

Hydrocarbons Under The Perspective of The EU F-Gas Regulation

Within the 2024 EU F-gas regulation, there are a series of bans for various RACHP (Refrigerant, Air Conditioning and Heat Pump) equipment types. Those related to DHPs are listed in Table 1. Orange shading indicates the difficulty in achieving charge limits for the larger capacity systems of AC&HP equipment, assuming non-mandatory limits in safety standards, whilst green shading implies that charge requirements are broadly achievable with R290. Except for items 8(e), “Other self-contained AC&HPs,” and 9(f), “AC&HP split systems > 12 kW”, it is expected that all equipment categories can be mostly satisfied with HCs.

Table 1 Comparison of required HC charges and values permitted by standards [1].

Year	Annex IV item[1]	Equipment category	Limitation[2]	R290 permitted[3] [kg]	
				IEC 60355-2-40	EN 378-1
2025	9(a)	Single split AC&HPs with < 3kg	No GWP > 750	1	1.5, 2.5
2027	8(b)	Plug-in room, monoblock AC, and self-contained HPs ≤ 12 kW	No GWP > 150 (or No GWP > 750)	1.0, 5.0	1.5, 5.0
2027	8(d)	Monoblock and self-contained AC&HPs, > 12 kW and ≤ 50 kW	No GWP > 150 (or No GWP > 750)	1.0, 5.0	1.5, 5.0
2029	9(b)	AC&HP split ATW systems ≤ 12 kW	No GWP > 150	1	1.5, 2.5, 5.0
2029	9(c)	AC&HP split ATA systems ≤ 12 kW	No GWP > 150	1	1.5, 2.5
2029	9(e)	AC&HP split ATA systems ≥ 12 kW	No GWP > 750	1	1.5, 2.5
2030	8(e)	Other self-contained AC&HPs	No GWP > 150 (or No GWP > 750)	1.0, 5.0	1.5, 5.0
2032	8(c)	Plug-in room, monoblock AC, and self-contained HPs ≤ 12 kW	No F-gases (or No GWP > 750)	1.0, 5.0	1.5, 5.0
2033	9(f)	AC&HP split systems > 12 kW	No GWP > 150	1	1.5, 2.5
2035	9(d)	AC&HP split systems ≤ 12 kW	No F-gases (or No GWP > 750)	1	1.5, 2.5

[1] The letter in parentheses refers to successive POM bans for each Annex IV item listed within Regulation 2024/573.
[2] Text in parentheses ("or No GWP > 750") refers to the condition "...except when required to meet safety requirements."
[3] Actual value depends upon system architecture (EN IEC 60355-2-40) or access class/system location classification (EN 378-1).

Possible Evolution to Widen The Application Range of Hydrocarbons

Wider implementation of HPs working with HCs depends critically on safety issues, and that point is strongly related to refrigerant charge reduction. In addition to more common R&D activities focused on improving HP efficiency and flexibility, refrigerant charge optimization will be a major research topic in future developments.

In that sense, strategies such as using condensers and evaporators with smaller internal volumes [3][4][5][6], minimizing liquid line lengths, and reducing oil in compressors [7] have shown potential for reducing refrigerant charge. Prototypes have demonstrated very low specific charges, as low as 10 g/kW, but the variety in results found in the literature suggests that further improvements are possible. However, most of these approaches still must address durability and feasibility issues before reaching the market.

As it has been explained, it is necessary to review the design criteria of all DHP system components to include the refrigerant charge as a design factor. But also, other aspects contributing to safety, like an analysis of the charge limit in the standards, total system response to external fires, effect of the overall housing design on room concentrations, methods to determine releasable charge, etc., must also be considered.

Conclusions

Hydrocarbons (HCs) are gaining renewed interest as refrigerants for DHPs as they are considered one of the safer environmental alternatives. While HCs are highly flammable and require careful safety considerations, revised international and European standards are now allowing their use in larger systems with larger charges, promoting the shift from synthetic fluids to HCs.

The sales of DHPs with HC-refrigerant (mainly using R290) are increasing, and they represented almost 20% of the German market in 2023. Many HP manufacturers are currently offering HCs DHP in their catalogs. Compressors and heat exchanger manufacturers are also optimizing their designs for HCs in such a way that the range of available products and applications is expected to grow in the next years.

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Topical Article

Review of Heating and Cooling Applications where HCs have been Introduced as Refrigerants and Future Perspectives of their Use

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By Francisco Barceló, Jose Gonzálvez (Spain), Emilio Navarro-Peris, Spain

This paper aims to review some applications where the use of hydrocarbons, either due to the operating environment or the refrigerant quantity required, is currently considered the most viable solution. Examples include household refrigerators, dryers, and small commercial refrigeration units. The paper will also explore other applications such as heat pumps, commercial refrigeration systems, refrigerated transport, and high-temperature heat pumps, where their use may eventually be adopted in part of the sector. Additionally, the review will address some existing barriers and potential development paths to expand their usage.

Introduction

In recent years, hydrocarbons such as propane (R290) and isobutane (R600a) have emerged as key players in the refrigeration industry, offering a natural and eco-friendly alternative to traditional synthetic refrigerants. With their low global warming potential (GWP) and excellent thermodynamic properties, hydrocarbons are becoming increasingly popular across a variety of sectors. From domestic refrigeration and air conditioning systems to commercial and industrial applications, hydrocarbons are being integrated into real-world systems as the most sustainable option under certain conditions. This article explores the diverse fields in which hydrocarbons are being successfully utilized as refrigerants today, highlighting their growing role in transforming the refrigeration landscape and contributing to a greener, more energy-efficient future. It concludes with considerations of possible technological evolutions that could extend the application range of HCs in HPs.

HCs as Refrigerants in Small Systems

Even though their good properties as refrigerants, because of their flammability, their use were abandoned when other non-flammable alternatives appeared in the market in the beginning of the 20th century, and it was not until the late of it, when the potential for serious environmental effects caused by the use of certain synthetic refrigerants was assessed, that the use of these types of refrigerants was reconsidered despite their flammability.

In this regard, and as described in [1], it is worth highlighting the significant role played by Greenpeace and the company DKK/Foron in overcoming the reluctance to adopt a flammable refrigerant like isobutane as the standard in domestic refrigerators in Europe. It was crucial for the standards to establish a charge limit to market these types of devices with safety guarantees. This charge limit of 150 g, although low, was sufficient to give manufacturers explicit safety guarantees, allowing the predominance of isobutane as the standard refrigerant in domestic refrigerators in Europe since the early 21st century. In this regard, more than 70% of the total produced domestic refrigerators are using R600a as refrigerant nowadays.

The experience gained over these years demonstrated the low risk of working with these systems, promoted the use of propane in other low-power applications while keeping the refrigerant charge below 150 g, and nowadays, there are more than 1 billion units installed all over the world.

Another example of the adoption of hydrocarbons as refrigerants is the transition to propane as the standard refrigerant that has been developed in domestic heat pump-assisted clothes dryers since 2015, when the first appliance was put into the market in Germany by Siemens. These systems commonly used other traditional refrigerants such as R134a or R407C, but environmental regulations combined with the good thermodynamic properties of R290 for this application aimed the manufacturers to adopt this natural refrigerant. The adaptation of the design of the cooling cycle to the use of R290, with a charge limitation of 150g, for systems with condenser capacities of around 3 kW included the re-design of the heat exchangers, adopting 5mm tubes, or the reduction of the oil charge in the compressor. Nowadays, most of the clothes dryers produced in Europe and Asia use R290.

Compact-portable air conditioning units are another application where the standard solution in Europe and Asia is to use R290 as refrigerant. These units present a sealed circuit, commonly using rotary compressors and a low-charge, less than 150 g, refrigerant circuit with typical capacities of up to 3.5 kW.

Hydrocarbons are also used in other small household appliances such as water coolers or wine refrigerators, although in this concrete application, the low power and slight temperature difference make other technologies, such as thermoelectric cooling, the standard solution.

HC in Commercial and Industrial Applications

Regarding the applications of R290 in commercial refrigeration, following the previous experience with domestic appliances, since the beginning of the 2000s, the use of HCs in self-contained refrigeration systems of relatively small sizes has been quite extended in Europe, going from display cabinets to freezers or vending machine coolers. Most of these units have been autonomous units, but also some manufacturers have developed semi-plug-in display cases featuring water systems for heat removal. Today, self-contained propane waterloop systems are gaining traction in commercial refrigeration worldwide, particularly in Europe, where manufacturers like Freor have implemented numerous installations.

This trend is also expected to be promoted by the update of the IEC 60335-2-89, which has increased the charge limit of this kind of system from 4xLFL to up to 13xLFL for self-contained systems in such a way that the cost of these units could be even more competitive as the number of refrigeration circuits used nowadays could be reduced. In fact, in a survey of OEMs, ATMOsphere [2] estimated that 3.2 million hydrocarbon-based retail cabinets have been installed in Europe as of December 2023. An increase of 10% from 2022, when there were an estimated 2.9 million.

In recent years, there has also been an increase in the number of products available for industrial chiller applications. Several manufacturers are offering chillers of 100 kW of capacity, and more than 5000 chillers have been reported installed in the EU, and some R744 (carbon dioxide) refrigeration systems in supermarkets in hot climates uses HCs for the mechanical subcooling part of the circuit.

Finally, the descarbonization of the industry is opening a new application field related to the high-temperature heat pumps to produce vapor at temperatures up to 200ºC, where HCs like butane, pentane, or isopentane can supply an efficient solution.

HC in Domestic Heat Pumps for Heating and Cooling

The normative for these applications was also updated some years ago by IEC 60335-2-40 and was approved in the EU last year. This normative introduces some concepts to make the safe use of HCs in the domestic sector more flexible, combined with the F-gas regulation approved last year has made some manufacturers [3] claim that HCs could be used in the heat pump market up to capacities of 70 kW and there are some projections that assume that Hcs will be the main refrigerant for heat pumps with a capacity lower than 12 kW in EU in future.

From that perspective, nowadays, it is easy to find liquid-to-water heat pumps of small capacities (6 kW) with 150 g of charge for indoors commercially available, and most important manufacturers in the EU have air-to-water heat pump models commercially available using R290 as a refrigerant. A wide review of the state of this sector is done in [4].
Nevertheless, in that sense, it should be pointed out that air-to-air split systems, which represent the most extended systems nowadays, still work mainly with F-gases, and even

though their use with HCs has been demonstrated safe for some small capacity applications, their presence in the market is not so significant, probably being its most important consideration to work the fact that in most cases their final installation must be done in situ. In that context, the experience on the introduction of these systems in India or China by some manufacturers like Midea, Haier or Clivet could be relevant for a wider diffusion of them.

Mobile and Transport Applications

Mobile HVAC (MAC) and refrigerated transport applications are key sectors regarding energy consumption and a number of installed cooling systems, where nearly every new vehicle for passenger transport (automobile, bus, or train) comes with one or several refrigeration units for passenger comfort or technical requirements. In fact, this sector was the first one in the EU to receive a directive to reduce the use of HFCs in 2006, and since then, HFOs and in some vehicles, R744 have been the dominant refrigerants.

Regarding the automotive industry, a transition is undergoing, where hybridization and electrification demand more efficient and reversible cooling systems, with the additional thermal management needs produced by the battery packs. In this regard, and as a consequence of the possible restrictions to the use of HFOs in the EU byEuropean Chemicals Agency (ECHA), some car manufacturers are exploring the use of R290 as a refrigerant. The most direct solution to ensure safety in the passenger compartment is using indirect cooling systems with an air-to-water heat pump, which feeds the climate control system and the battery thermal management system. This is the approach followed by some manufacturers like Ford and Denso for electric vehicles, considering the requirements of a global solution, including thermodynamic performance and regulatory limitations. Tata is developing in collaboration with Mahle, in the framework of a United Nations Industrial Development Organization (UNIDO) project, secondary loop MAC (mobile air conditioning) and battery cooling systems with R290 for EVs in India.

The transport of people industry is also considering the switch to HCs, and the most recent developments arriving on the market are using propane as refrigerant. In this sector, cooling systems also need to cover several services, but the typical solution is to have different systems for each requirement. For instance, in electric buses, in addition to the cooling system for passengers, an additional thermal management system consisting of an air-to-water heat pump is needed to control battery temperature. Or in trains, additionally to climate control, galleys require cooling for food and beverages.

Several railway services are starting to use HVAC systems with R290. In September 2024, Mitsubishi Electric Klimat Transportation Systems S.p.A received an order from Siemens Mobility GmbH for 1350 HVAC systems to be installed in in next-generation trains of the S-Bahn rail system in Munich, Germany. Stadler Polska Sp. z o.o. placed an order of 80 R290-HVAC units to Liebherr Transportation Systems in June 2024 for equipping 20 Flirt trains, which will serve regional routes in Helsinki, Tampere, and Lahti. Deutsche Bahn is testing 16 R290 units in two ICE3 neo trains, reporting no issues with the refrigerant and expecting to operate more than 2000 units using propane by 2027. Other railway HVAC systems manufacturers, such as Hispacold or Konvekta, are also selling or developing R290 units. It is relevant to point out that some of these systems are using direct refrigerant circuits and have shown that with under the right design consideration, it could be a feasible alternative. Regarding other uses of cooling in railway, new generation ICE4 German high-speed trains will be equipped with R290 cooling systems at their galleys, manufactured by Wölfle GmbH. Manufacturers are also developing indirect cooling systems for buses and electrical buses, where propane is an excellent option due to its high performance and availability to work at a wide range of temperatures. Copeland presented its YRH(V)*KTG range of horizontal scroll compressors for R290 and transport applications, focused on bus and railway applications in the same way as Bitzer did with its SPEEDLITE ELV52 PRO compressor.

Even in the sector of marine transport that could be more resistant to the introduction of flammable refrigerants, there are some initiatives like [5] which are promoting the use of R290 in this sector, which nowadays is still dominated by R134a, but it is facing a transition to low-GWP refrigerants.

Conclusions

The growing concern for the environment and the catastrophic effects that the emission of greenhouse gases can have on our society has led to reconsider the use of flammable refrigerants in the heating and cooling sector.

In that context, this paper has shown that the use of HCs is going to be the dominant refrigerant for some applications, and although their use in the past was restricted to low-capacity applications, nowadays some higher capacity applications like chillers of capacities of 100 kW are considering it as a reliable alternative.

Even in the transportation sector, which was reluctant in the past to the use of flammable refrigerants, is beginning to use it, and from the accumulated experience, it has seen that it is possible to design safe HCs systems without a significant increase in the cost. It is convenient to point out that up to now, the design of refrigeration systems has not considered in deep the operation with flammable refrigerants. But there are aspects like refrigeration circuit design with the perspective of charge minimization, charge release, techniques to avoid flammable atmosphere, or even the increase of prepared technicians that could extend their use to other applications.

Finally, trying to make a perspective on the future, the adoption of HCs and other natural refrigerants have the advantadge that once the transition to those refrigerants is made for an application/sector in which their introduction is feasible, there will be no more future change of refrigerant for those systems and the successful case of the adoption of HCs in domestic refrigerators support that.

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Topical Article

Modeling Leaks of Flammable Refrigerants

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By B. Palm, Sweden, J. Esmaeelian, Sweden, K. Nawaz, USA, D. Colbourne, Great Britain

Hydrocarbons (HC) are being introduced as refrigerant in heat pumps and AC systems, as a part of the phase-down of synthetic refrigerants. As HC are highly flammable, standards are being refined for their safe use. To better understand the risks, computational fluid dynamics (CFD) can be used to determine the concentrations of flammable refrigerants during the release in case of a leak. In this article, we will give a brief overview of work done in the US, as well as provide examples of results which have been achieved using CFD in Europe. This work is part of the IEA HPT Annex 64 on Safety Measures for Flammable Refrigerants.

Introduction

Global warming requires phase-out of fossil fuels, and most countries are planning to be carbon-free by 2050. This requires decarbonization and electrification of the complete energy system. A large share of fossil fuels is used today for heating, in buildings, and industry. In the future, heating needs to be based on heat pumps instead, and the IEA has suggested that the installation of 600 million heat pumps is required by 2030 [1]. At the same time, synthetic refrigerants are being phased down, and in Europe, phased out completely for smaller systems, due to their high GWP and / or because they belong to the PFAS group of substances, of which many have been found to be harmful for the environment and for human health. For these reasons, there is broad interest in using natural refrigerants, and in particular, hydrocarbons are being introduced as environmentally safe alternatives. However, the flammability of these fluids needs to be taken seriously, and this is the topic of the IEA HPT Annex 64 on Safety Measures for Flammable Refrigerants. One of the activities within the Annex is investigating leakage scenarios, i.e., how flammable refrigerants (class A3) spread in a confined space in the event of a leak. In this article, we will present some findings, partly from our literature review and partly from the work within the Annex.

Findings from Investigations in The US

In the United States, A3 refrigerants, such as R290 (propane), have garnered significant attention as viable alternatives to high-GWP refrigerants due to their ultra-low global warming potential and excellent thermodynamic efficiency. These refrigerants offer a compelling pathway toward meeting climate goals by significantly reducing the carbon footprint of heating, ventilation, air conditioning, and refrigeration (HVAC&R) systems. However, the high flammability of A3 refrigerants, as designated under ISO 817 (also ASHRAE Standard 34), raises flammability concerns that necessitate rigorous and systematic risk assessment before widespread adoption. To this end, numerous U.S.-based studies and regulatory initiatives have focused on evaluating the associated flammability risks and developing protocols to ensure safe application.

In particular, the U.S. Department of Energy (DOE), in collaboration with national laboratories such as Oak Ridge National Laboratory (ORNL), has spearheaded experimental and modeling research to understand potential hazards and mitigation strategies. A comprehensive study by ORNL [1] examined refrigerant leak scenarios in both residential and commercial systems, demonstrating that the formation of flammable concentrations is typically localized and short-lived, especially when modern ventilation and leak containment strategies are employed. These findings underscore that the risk of ignition can be effectively managed through proper system design. The Air-Conditioning, Heating, and Refrigeration Technology Institute (AHRTI) further advanced this understanding through its Flammable Refrigerants Research Program. This initiative encompassed a wide range of real-world simulations involving leak ignition tests, charge size validation, and ignition source mapping in diverse room configurations. The resulting data confirmed that adherence to charge size limitations and the elimination of nearby ignition sources substantially mitigates flammability risk [2]. Similarly, Underwriters Laboratories (UL) responded to these findings by updating UL 60335-2-40, incorporating specific provisions for equipment using A3 refrigerants [4]. The revised standard mandates enhanced construction features and defines charge thresholds that help ensure safe deployment in residential and light commercial settings.

Complementing these empirical efforts, the National Institute of Standards and Technology (NIST) developed detailed computational models to quantify ignition probability and evaluate thermal consequences following a refrigerant release. Lemmon and McLinden [4] concluded that, under standard ventilation conditions and with proper leak detection technologies in place, the likelihood of ignition is minimal. These insights have been instrumental in shaping risk-informed design practices. ASHRAE’s ongoing research projects, such as RP-1806 and RP-1839, have also provided critical data on ignition thresholds and flame propagation behaviors specific to A3 refrigerants [5]. The results reinforce that while flammable, these substances can be safely managed within confined environments, provided there is robust adherence to design codes and ventilation standards.

Finally, the U.S. Environmental Protection Agency (EPA), through its SNAP (Significant New Alternatives Policy) Program, has facilitated the conditional approval of A3 refrigerants like R290 in various end-use applications. Rule 23 [7] outlines specific use cases and safety conditions under which A3 refrigerants are deemed acceptable substitutes. Taken together, these research findings and policy developments reflect a growing consensus that A3 refrigerants, despite their flammability, can be integrated safely into RACHP (Refrigeration, Air Conditioning and Heat Pump) systems when supported by engineering best practices, updated safety standards, and continued innovation in leak detection and system architecture.

Examples of recent CFD studies

Two recent articles demonstrate clearly what results can be achieved by using CFD (Computational Fluid Dynamics) simulations to determine the hydrocarbon concentrations in a confined space after a leakage [8],[9]. Some of the results are presented here.

The simulations were conducted using ANSYS FLUENT 2023, employing the finite volume method with a second-order upwind difference scheme. The COUPLED algorithm resolved the pressure-velocity coupling, and turbulence modeling utilized both the standard k-epsilon (kε) and SST k-omega (kω) models. After validation against experimental data from Colbourne and Suen [10], the SST k-omega model was selected.

To examine refrigerant dispersion during unintentional leakage, simulations were performed in a small room with dimensions of X: 3 m, Y: 2.5 m, and Z: 3.5 m, with the AC unit mounted at y = 1.8 m on the middle of the wall (z = 0).

Refrigerant leakage was assumed from a hole on the right-hand side bend of the indoor unit (IDU) coil, occurring at a constant mass flow rate, as in the study by Colbourne and Suen [10]. The leaked refrigerant mixed with return air inside the IDU and was expelled with an average velocity of 1.3 m/s and a flow rate of 0.053 m^3/s.

According to IEC 60335-2-89, as can be seen in Figure 1, at a saturation temperature of 35°C, the leakage rate of R290 (propane) is 2.73 times that of R600a (isobutane). This results in R600a taking longer to fully discharge.

Across all pairs, R290 consistently shows higher concentrations than R600a, as can be seen in S1, S3, S5, and S7, with more intense and widespread gradients. When the fan is operational (S1, S2, S5, S6), refrigerant dispersion increases, reducing localized LFL percentages compared to scenarios without fan operation (S3, S4, S7, S8). The fan aids in mixing leaked refrigerant with room air, preventing high concentrations near the source. Conversely, when off, the refrigerant accumulates near the floor, increasing localized flammability risks.

Scenarios S7 and S8, where the IDU is at floor level and the fan is off, show the highest flammable volumes due to refrigerant settling. In contrast, when installed at a standard height (S5, S6), refrigerant disperses more before settling, reducing flammable volumes.

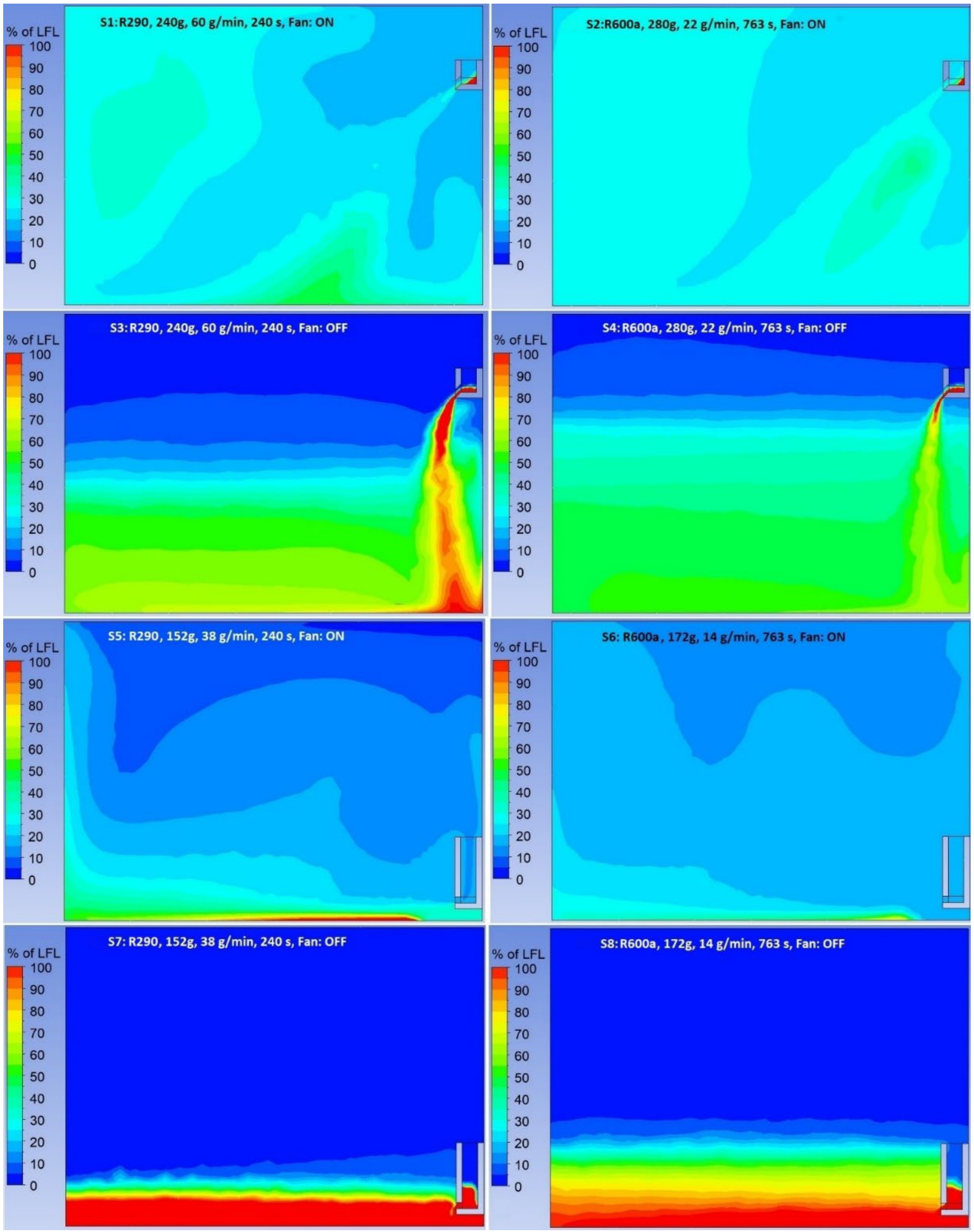

Figure 1: Refrigerant concentration contours after complete leakage. The middle plane was chosen for visualization to provide a comprehensive representation, though the highest concentration is in the leakage plane on the right side of the evaporator. Some regions exceed 100% of the lower flammability limit (LFL), but a 0-100% range was used to ensure comparability. The deepest red shade indicates concentrations surpassing 100% of the LFL.

Colbourne has published several papers on simulations of leakage scenarios. In an unpublished report, he shows that the maximum limit of 26xLFL, corresponding to 1 kg of propane, mentioned in IEC 60355-2-40 has no rational basis. A CFD model is used to demonstrate this. The model has been validated as reported in [10].

Here we will present the results only for an "unventilated" case, i.e., release under quiescent conditions. The indoor unit is installed at a height of 1.5 m, rooms are sealed except for an opening on the ceiling for relief of excess pressure due to introduction of refrigerant (although this is not included for consequence calculations).

Two leak rates were used, being instantaneous releases of 60 g/min and 180 g/min of propane. A series of CFD calculations were carried out to generate flammable volumes, flammable mass, and flammable times. For each set of conditions, several cases ranging up to about 4 kg were calculated and best fit curves plotted to enable a smooth estimation across the incremental increases in refrigerant quantities and room sizes.

Results for flammable volume vs time for the low and high mass flow cases are shown in Figure 2 and Figure 3, respectively. Generally, the flammable volumes for the high mass flow releases are about ten times those of the low mass flow. On the other hand, the time a flammable concentration persists is much shorter in the case of the large leak rate.

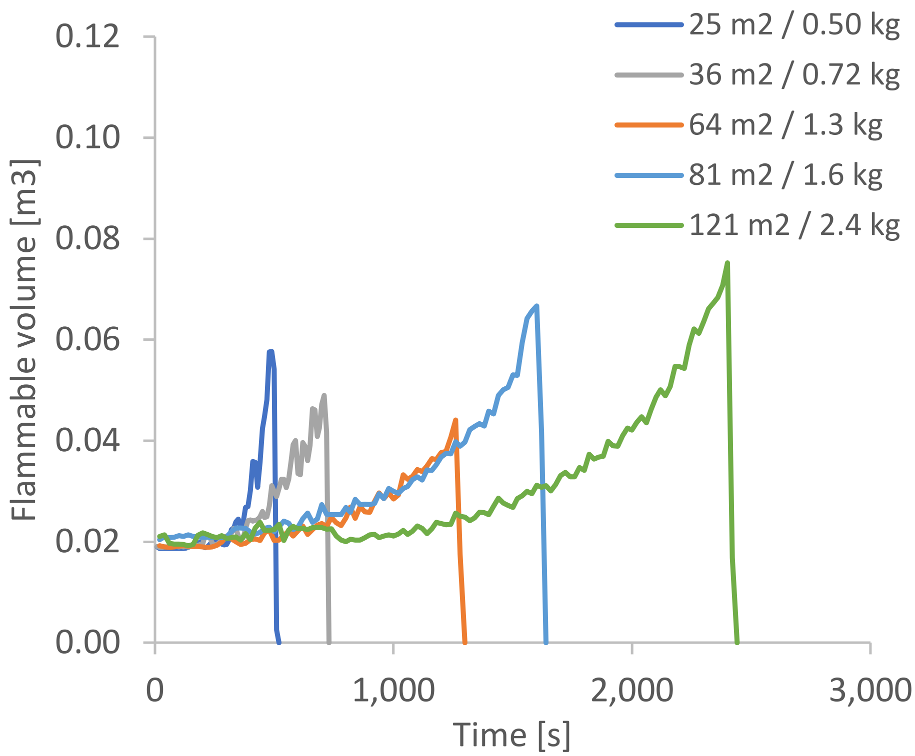

Figure 2: Flammable volume and time for low mass flow rate releases at 1.5 m unit height.

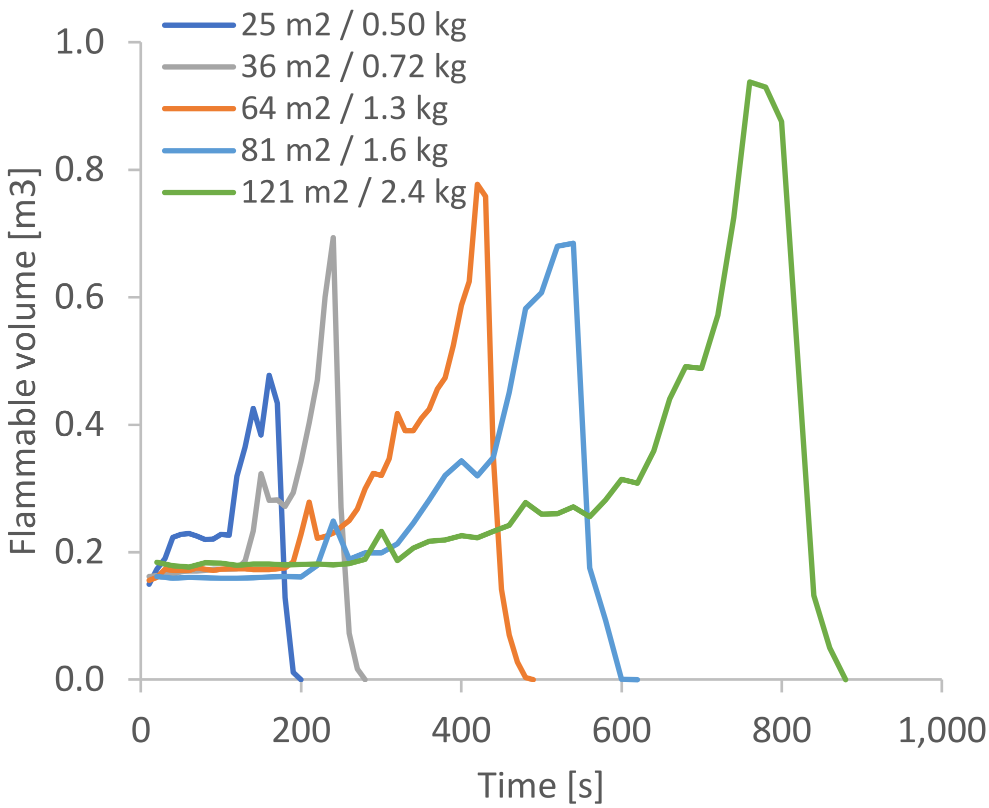

Figure 3: Flammable volume and time for high mass flow rate releases at 1.5 m unit height.

Conclusions

Determining refrigerant concentrations in a room after a leak of flammable refrigerant is important for understanding the risks. Numerical calculations, CFD, is an excellent tool for this purpose. Several reports and scientific papers have been published on this topic, publications which can be used as the basis when updating regulations and standards. In this article, we reported on some of the work done and gave a few examples of what type of results can be achieved. In particular, we showed that a leakage of isobutane (R600a) can be expected to give lower concentrations than propane (R290), leaking through a hole of the same size. We also showed the importance of having a fan in the room, and gave examples of how large the flammable volumes can be expected to be, and how long such volumes can be expected to exist, during leakages of different amounts of propane in rooms of different sizes.

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Topical Article

Oil Meets Cool: Inside the World of Lubricant-Refrigerant Properties

DOI: 10.23697/ypqs-qr32

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The interaction between lubricants/oils and refrigerants plays a pivotal role in the performance and reliability of HVAC and refrigeration systems, yet it is often overlooked in system design. This article explores the dual impact of oil and natural refrigerants mixtures on thermophysical properties and heat transfer. It highlights how dissolved refrigerants affect lubricant behavior in the compressor, and conversely, how oil presence in the circulating refrigerant influences system efficiency. Through analysis of miscibility curves and thermodynamic behavior, particularly with propane (R290) and various synthetic oils, the article emphasizes the importance of selecting appropriate refrigerant-oil combinations. A comprehensive understanding of these interactions is essential for optimizing system performance and ensuring stable lubrication.

Introduction

In refrigeration and HVAC systems, the interaction between lubricants/oils and refrigerants is often overlooked during design simulations, which adversely affects the performance of the system. The amount of oil that dissolves into the circulating refrigerant can directly affect the system's Coefficient of Performance (COP) and alter the refrigerant's thermophysical properties. Conversely, the amount of refrigerant that mixes with compressor lubricant in the crankcase can have a major impact on key oil properties like viscosity, miscibility, and thermal stability. Figure 1 shows clearly that low viscosity values lead to poor lubrication (film thickness) and low volumetric efficiency, whereas high viscosity values lead to good lubrication but high frictional losses or low mechanical efficiency.

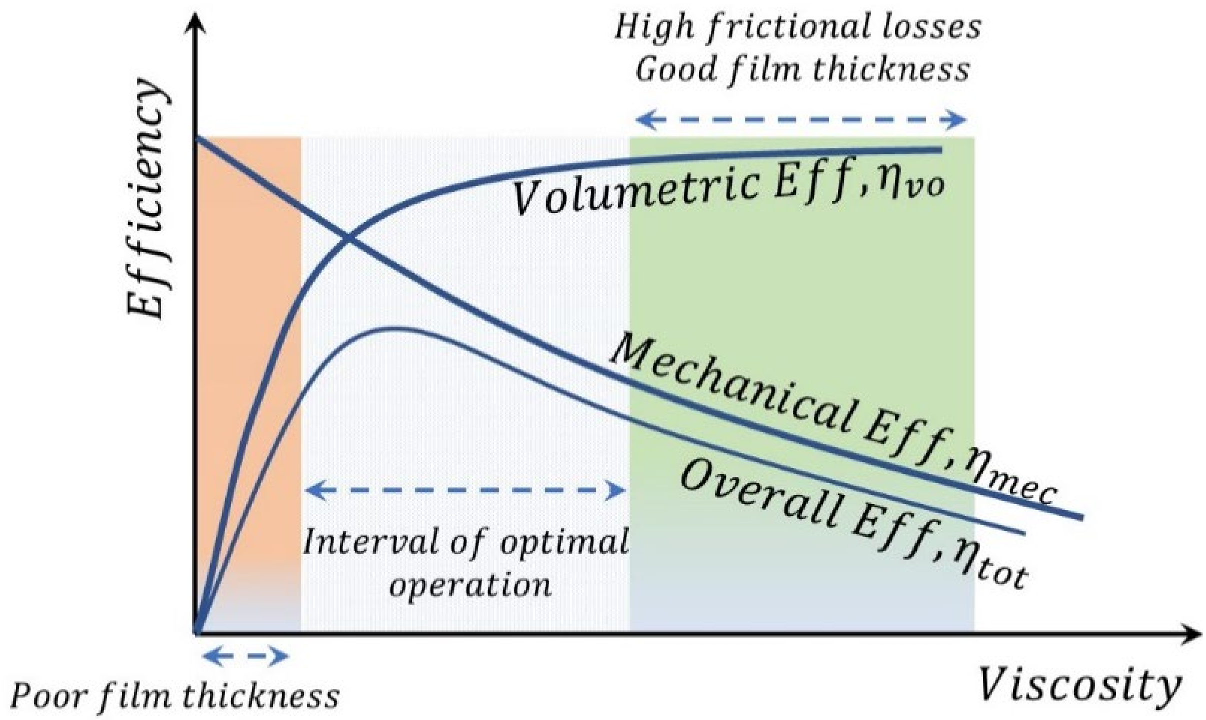

Figure 1: The effect of viscosity on compressor's efficiency

Lubricants/oils frequently used for synthetic or natural refrigerants are mineral oils (MOs), alkylbenzenes (ABs), Poly-alpha-olefins (PAOs), poly-alkylene-glycols (PAGs), polyvinyl-ethers (PVEs), and poly-ol-esters (POEs). Rudnick's book "Synthetics, Mineral Oils, and Bio-Based Lubricants, Chemistry and Technology," puts together an excellent introduction to all types of synthetic lubricants.

The relationship between lubricants and refrigerants should be clearly defined by distinguishing between the Lubricant-Refrigerant Mixture (LRM), which focuses on the effect of refrigerants on lubricants within the compressor sump, and the Refrigerant-Oil Mixture (ROM), which examines how dissolved oil in the circulating refrigerant influences the refrigeration system and alters the refrigerant's thermophysical properties. Figure 2 highlights key factors that must be addressed, including miscibility and thermal behavior, which are critical in the evaporator, variations in oil content can shift the refrigerant's boiling point, and oil retention in the evaporator and condenser can reduce heat transfer efficiency, ultimately lowering the system's cooling capacity and coefficient of performance.

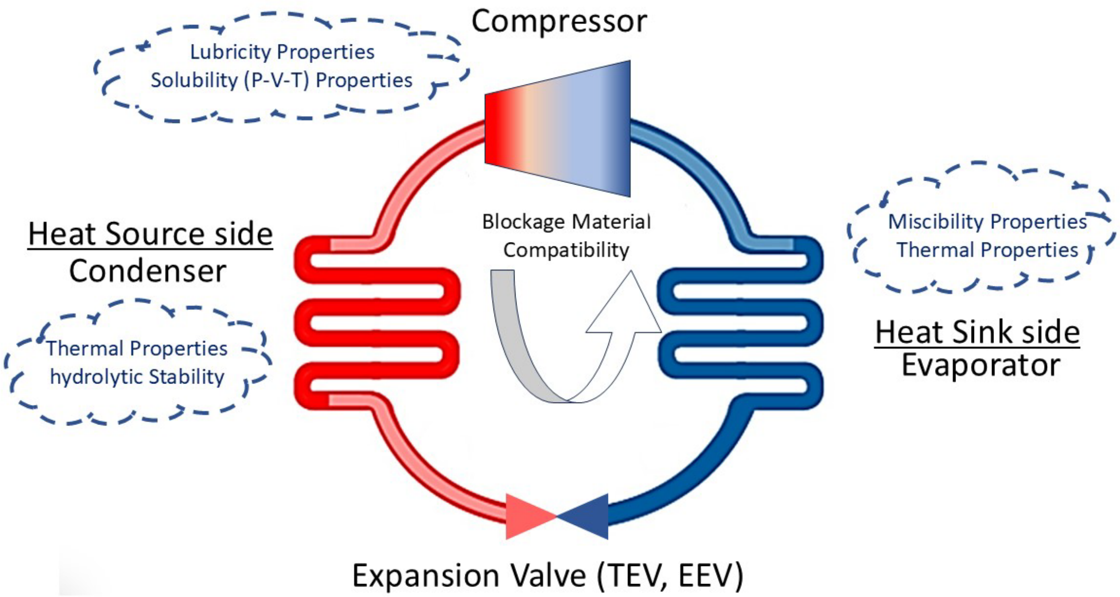

Figure 2: Oil-refrigerant issues in heat pump components

Lubricant-Refrigerant Mixture (LRM) Properties
The effect of the vapor or liquid refrigerant within the lubrication fluid in the compressor sump changes the properties of the lubricants. These properties are dynamic viscosity, solubility, kinematic viscosity, viscosity index (VI), lubricity, pour point, thermal and hydrolytic properties, and oxidation stabilities. Only dynamic viscosity will be further explored in this article.

Dynamic viscosity (μ_{RLM}) selection depends upon minimum film thickness required to avoid wear surfaces, maximum allowable viscous drag, minimum sealing, minimum flow rate, and minimum variation within the operating envelope [1]. The viscosity of the lubricant in the presence of any refrigerant may decrease as much as an order of magnitude, since the refrigerant viscosity is typically 2 to 3 orders of magnitude smaller than that of oil [2]. LRM viscosity can also be obtained from specific *PVxT* charts. The parameters used to construct these charts are pressure, temperature, solubility, and kinematic viscosity. The combined *PVxT* data that includes isobaric curves is called the Daniel Plot [3].

The plot of any mixture is derived from refrigerant solubility data (x), density data (ρ), and viscosity data versus temperatures. To get the dynamic viscosity of a specific LRM:

1. Pressure and temperature are selected first.
2. Pressure versus temperature is used to measure solubility parameters.
3. Solubility versus temperature is used to measure kinematic viscosity (KV or $\vartheta = \mu/\rho$, cSt) and density parameters.
4. Dynamic viscosity (μ, cP) is obtained by the product of KV and density.

Other ways to obtain kinematic viscosity (ϑ_{RLM}) can be given analytically by relating the viscosity of the lubricant and the refrigerant as in equation (1) [4].
where (γ_{ref}) is the refrigerant mass fraction.

$$ln\, \vartheta_{RLM} = (1 - \gamma_{ref}) * ln\, \vartheta_{lubricant} + \gamma_{ref} * ln\, \vartheta_{ref}$$

Eq. (1)

Refrigerant-Oil Mixture (ROM) Properties

The ROM properties do not differ from LRM properties, but miscibility-solubility properties and the thermo-physical properties are the most critical issues that need to be evaluated to understand the effect of the mixture on the energy efficiency of the systems and their performance.

Miscibility - Solubility

Miscibility is the property of two substances that completely mix in all proportions or concentrations to form a homogeneous, clear solution, where solubility is the ability of one component (the solute) to dissolve in the other component (the solvent) till saturation point or phase separation occurs. An example of miscible solutions is water and alcohol. The chemical miscibility of the refrigerant-oil mixture is a good indicator of how well the refrigerant will help move the oil around the system. We must indicate that the amount of oil circulated with the refrigerant is small, but its effect is crucial. The miscibility property is crucial to prevent phase separation between the oil and refrigerant mixture, especially in the evaporator.

Miscibility is typically studied by mixing known concentrations of refrigerant and oil and lowering the temperature until a phase separation is observed [5]. The results are used to plot a curve of concentration versus temperature, which indicates the miscibility boundaries before causing separation of an oil-rich phase. The curve shows the amount of refrigerant mixed with the oil-rich phase (solubility of refrigerant in oil). Knowing where the separation phase will form and how much refrigerant is needed to dilute an oil-rich phase can help determine which types of oils are acceptable for use with a given refrigerant [6].

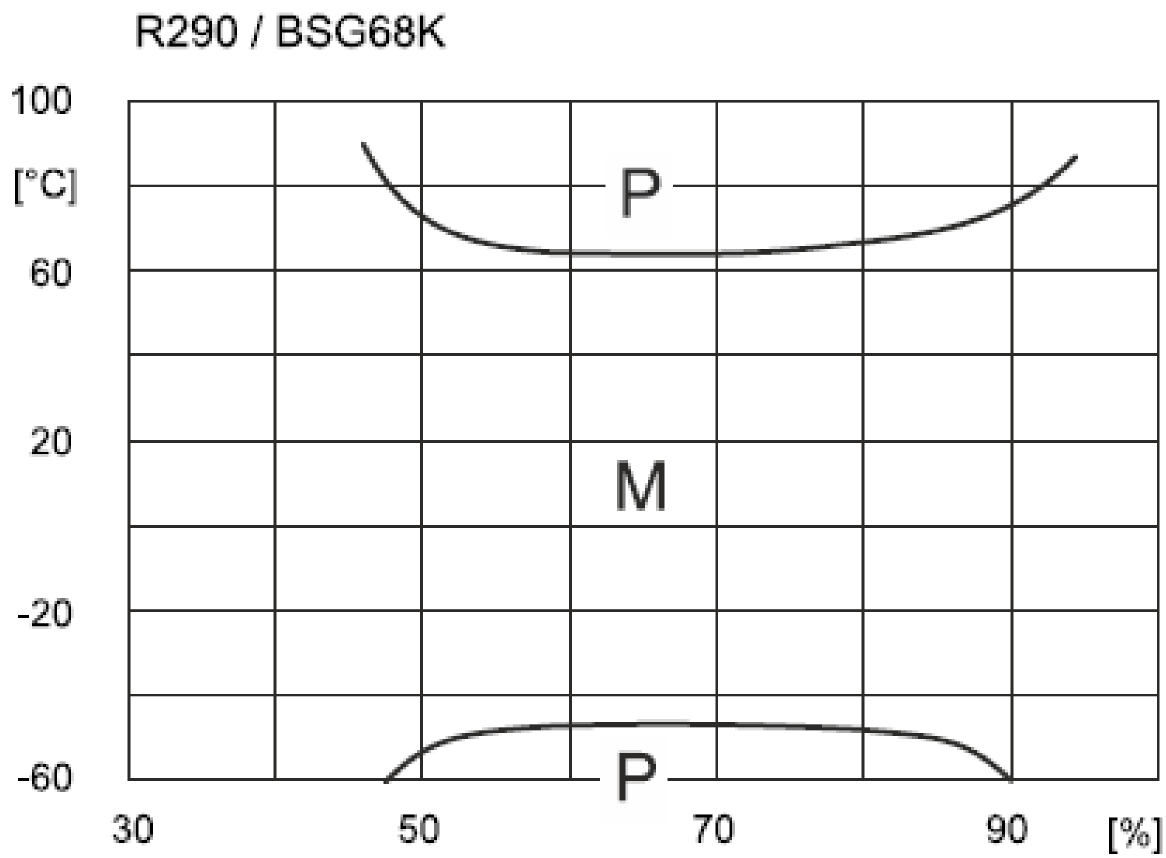

Figure 3: Miscibility gaps for R290 (Image courtesy of Bitzer Compressors)

Figure 3 shows the miscibility curves of PAG oils (BSG58K) with refrigerant R290; the figure has been taken from Bitzer compressors [7], where the horizontal axis represents the oil mass concentration. The target zone of full miscibility (M) spans from -40℃ to 60℃ across all oil concentrations, while the phase separation regions (P) are located at the top and bottom of the figure.

According to Bitzer, PAO oils like SHC226E offer excellent miscibility with refrigerants, remaining fully miscible from -60°C to 100°C across all oil concentrations. This prevents phase separation, ensuring stable lubrication, efficient oil return, and consistent thermophysical properties, key for reliable performance in refrigeration and heat pump systems. The broad miscibility range also simplifies system design and enhances flexibility, making SHC226E ideal for applications with wide temperature variations.

Thermo-Physical Properties

The refrigerant-oil mixture can lead to reduced heat transfer coefficients, decreased cooling or heating capacity, and a lower COP for the heat pump system. Understanding these thermophysical property changes is essential for accurate modeling, simulation, and design optimization of heat pump cycles.

When the working fluid in a heat pump or refrigeration system shifts from a pure refrigerant, whose thermophysical properties are well-established and well-understood, to a mixture of refrigerant and lubricating oil, the behavior of the fluid becomes more complex and less predictable. This transformation introduces new challenges in system analysis and design, as the properties of the refrigerant-oil mixture are strongly dependent on both the type of oil used and its concentration within the cycle.

One of the key impacts of this change is on the heat transfer processes occurring in critical components such as the evaporator and condenser. The presence of oil alters fluid properties such as viscosity, thermal conductivity, specific heat, and boiling characteristics, all of which directly influence heat transfer efficiency. In some cases, the oil can enhance heat transfer by improving film stability or modifying surface tension, but more often it impairs performance by increasing thermal resistance and reducing the effective heat transfer coefficient. The overall effect, whether beneficial or detrimental, depends largely on the oil concentration, operating conditions, and the nature of the refrigerant – oil interaction. According to Raoult's Law, the introduction of oil into the refrigerant increases the boiling point of the mixture compared to that of the pure refrigerant. This elevation occurs because the oil effectively lowers the vapor pressure of the refrigerant, requiring a higher temperature to achieve phase change. This shift can disrupt the thermal balance within the evaporator and impact system control strategies based on pressure–temperature relationships.

Moreover, during the evaporation process, the oil holds a portion of the refrigerant dissolved or trapped within the liquid phase. As a result, less refrigerant is available to undergo phase change, leading to a reduction in latent heat absorption. This directly decreases the heat-carrying capacity of the working fluid, which in turn lowers the cooling or heating output of the system and can negatively affect COP.

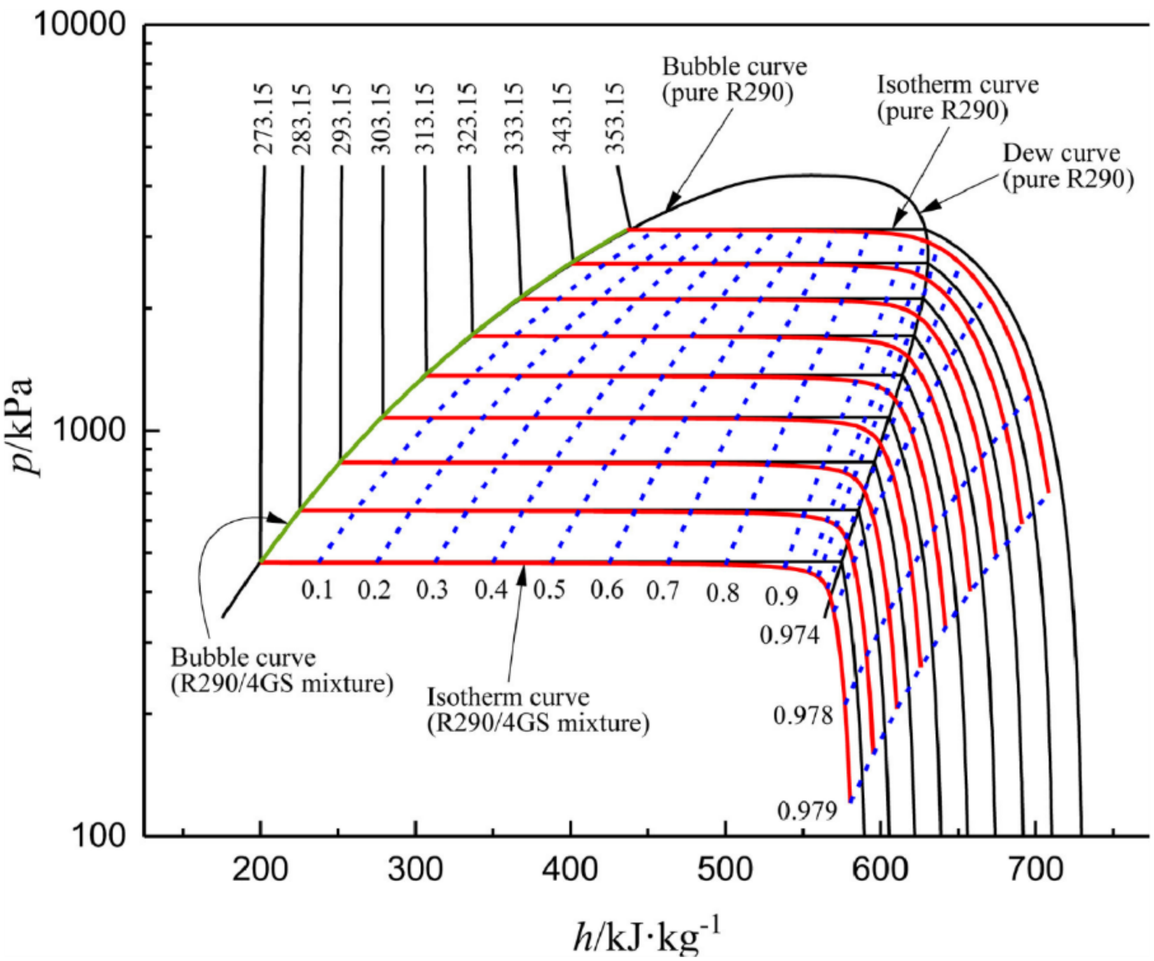

Figure 4: Enthalpy diagram for a 4% mixture of R290 and 3GS mineral oil *(Image courtesy of Wang et al., 2021)*

Figure 4 shows the log(P)-h diagram for a mixture of R290 and mineral oil 3GS for oil circulating mass fraction of 4% [8]. The figure illustrates the thermodynamic behavior of the working fluid, with black lines representing pure refrigerants and red lines corresponding to the refrigerant–oil mixture. It clearly demonstrates that, unlike pure refrigerants, the vapor line in the vapor–liquid mixture region is less distinct when oil is present, as the oil tends to remain in the liquid phase throughout the process. During evaporation, two distinct regions can be identified. Initially, the mixture behaves similarly to a pure refrigerant, exhibiting isothermal characteristics in the early stages of the evaporator. However, as evaporation progresses and the local concentration of oil in the remaining liquid increases, the behavior begins to deviate. This results in a departure from the isothermal path, with the mixture curve approaching the vapor line of the pure refrigerant. This shift highlights the influence of oil accumulation on phase change behavior and heat transfer performance.

Conclusions

Understanding the interactions between lubricants/oils and refrigerants is essential for optimizing the performance, reliability, and energy efficiency of HVAC and refrigeration systems. The presence of oil within the refrigerant circuit can significantly influence key thermophysical properties such as viscosity, boiling point, and heat transfer capacity, often leading to reduced system efficiency if not properly accounted for. Both miscibility and solubility play crucial roles in ensuring smooth oil circulation and preventing phase separation, particularly under varying temperature and pressure conditions. As the industry moves toward low-GWP refrigerants, careful selection and evaluation of mixtures combinations become increasingly important.

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National Market

Netherlands: Heat Pump Market Report

DOI: 10.23697/n1xb-cb66

By Frank Agterberg, PhD, MBA, Dutch Heat Pump Association, and Hrvoje Medarac, PhD, Dutch New Energy Research

The 2024 calculation of the expected reduction of CO2 emissions in the Dutch built environment in 2030 is 48% compared to 1990. The reduction of emissions between 2023 and 2030 is mainly due to improved insulation and expansion of the installed base of heat pumps. The chance of meeting the required emissions reduction of 59% in 2030 in this segment is estimated at 10%. However, the sector's target thus requires a step up of another 11% points.

Introduction– The Role of Heat Pumps in The Energy Transition

Public policies across the globe are stimulating heat pumps to replace natural gas boilers as they deploy (renewable) electricity with a high efficiency: the ratio of useful heat versus the primary electrical energy used, the so-called coefficient-of-performance (COP), generally is in the range of 3-6 and may be even higher with relatively high-temperature thermal sources such as shallow geothermal systems - aquifer or borehole thermal energy sourced heat pumps. The Netherlands' subsoil is particularly suitable for the latter. The share of electricity production from renewable sources in the Netherlands in 2024 was 53% [1], thus rendering heating by heat pumps in the range of 84% to 92% sustainable. Since the ban on new gas connections in 2018, heat pumps in the Netherlands have been the standard for individual heating (and cooling) systems in new dwellings, having a market share of 75%. This technology is gradually on its way to also become the standard in renovations, with a growing progressively yet fluctuating market share in gas-boiler replacements ranging from 13 to 24% in recent years.

This article describes the recent history, current status, and near-term outlook for the Dutch heat pumps market development.

Dutch Heat Pumps' Market Developments

Heat Pumps in Residential Buildings

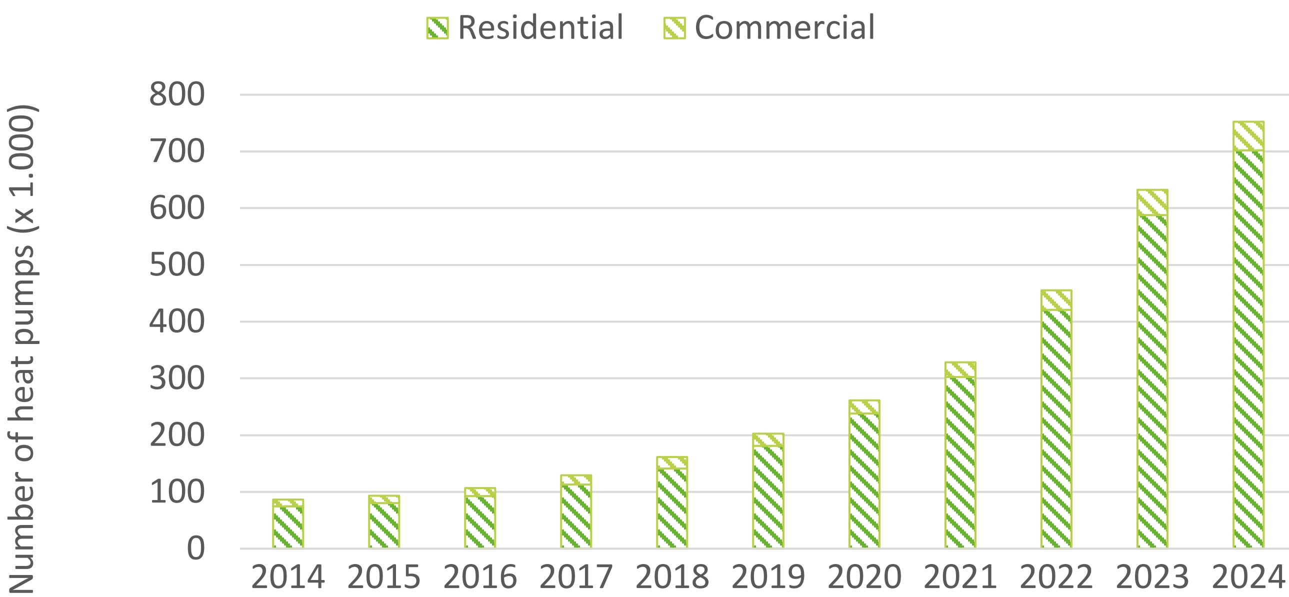
The Netherlands currently has some 8.2 million individual homes [2], of which in 2024, some 700.000, 1 in 12, deployed an individual heat pump. The market share of individual heat pumps in newly built dwellings is 75% on average, just over 70.000 new homes yearly.

The Dutch government's ambition is to raise new build dwellings to 100.000 annually. Public energy transition goals aiming for 1,5 million heat pumps in dwellings in 2030, depend mainly on renovations, targeting at least 1 million (hybrid) heat pumps, which should replace natural gas boilers in existing dwellings by 2030. Whilst the renovation market grew rapidly in 2022 and 2023, 'helped' by extremely high natural gas prices and a generous subsidy scheme, the market declined by 30% in 2024 from a combination of factors, including relatively low and relatively stable natural gas prices, political uncertainties, and fear of electricity grid congestion.

Heat Pumps in Commercial Buildings

Whilst the total amount of space to be climatised more sustainably is in the same range as the overall domestic buildings' supply, the current growth rate of heat pumps in commercial buildings' renovations is much smaller than in residential buildings. The heat pumps market for non-residential, i.e., commercial, buildings shows different dynamics. Policy targets and instruments are less specific than for residential applications. Three different financial schemes are the 'carrots' aimed at stimulating owners. Legally required reporting of a commercial building's energy performance, combined with mandatory measures having a payback time of less than 5 years, forms the 'stick' forcing renovations. Indoor climate control systems in commercial buildings require more one-off specific designs and are thus generally less standardized, contrary to dwellings' installations.

In 2024, the installed base of heat pumps [3] in the Netherlands, the number reached 752.000 [4] with a total installed thermal capacity of 6,9 GW. Out of this, 702.000 or 93% of the number of heat pumps were in residential and 50.000 or 7% in the utility sector, as presented in Figure 1.



	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Commercial	12	13	14	16	20	22	23	26	34	44	50
Residential	75	80	93	113	141	181	238	303	421	588	702

***Figure 1*: Total number of heat pumps in the Netherlands (Source: Nationaal Warmtepomp Trendrapport 24/25, DNE Research)**

After a decade of structural increase in the sales of heat pumps in the Netherlands, reaching 179.000 for both residential and commercial buildings in 2023, the overall sales in renovation plus new buildings decreased by 30% to 125.000 in 2024, as shown in Figure 2.

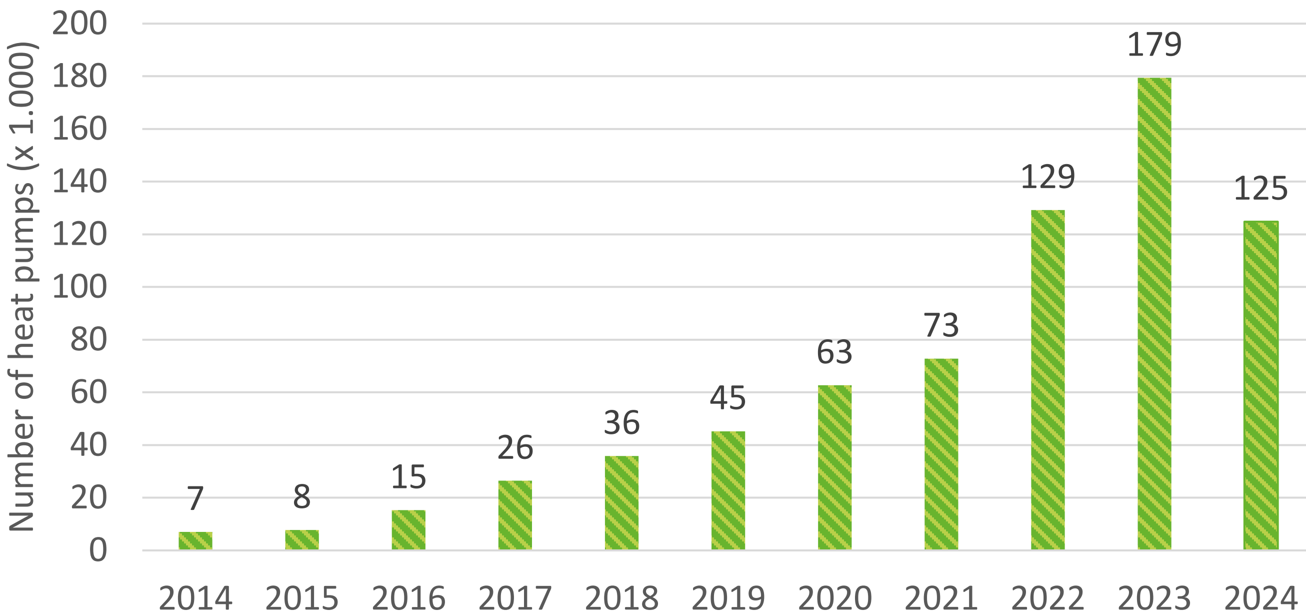


***Figure 2*: Annual sales of heat pumps in the Netherlands (Source: Nationaal Warmtepomp Trendrapport 24/25, DNE Research)**

But this decrease was not consistent in all sectors. As can be seen in Figure 3, the annual added capacity in the residential sector decreased by 31% from 923 MW in 2023 to 637 MW in 2024, while the added commercial scale capacity decreased by only 12%, reaching the capacity of 417 MW.

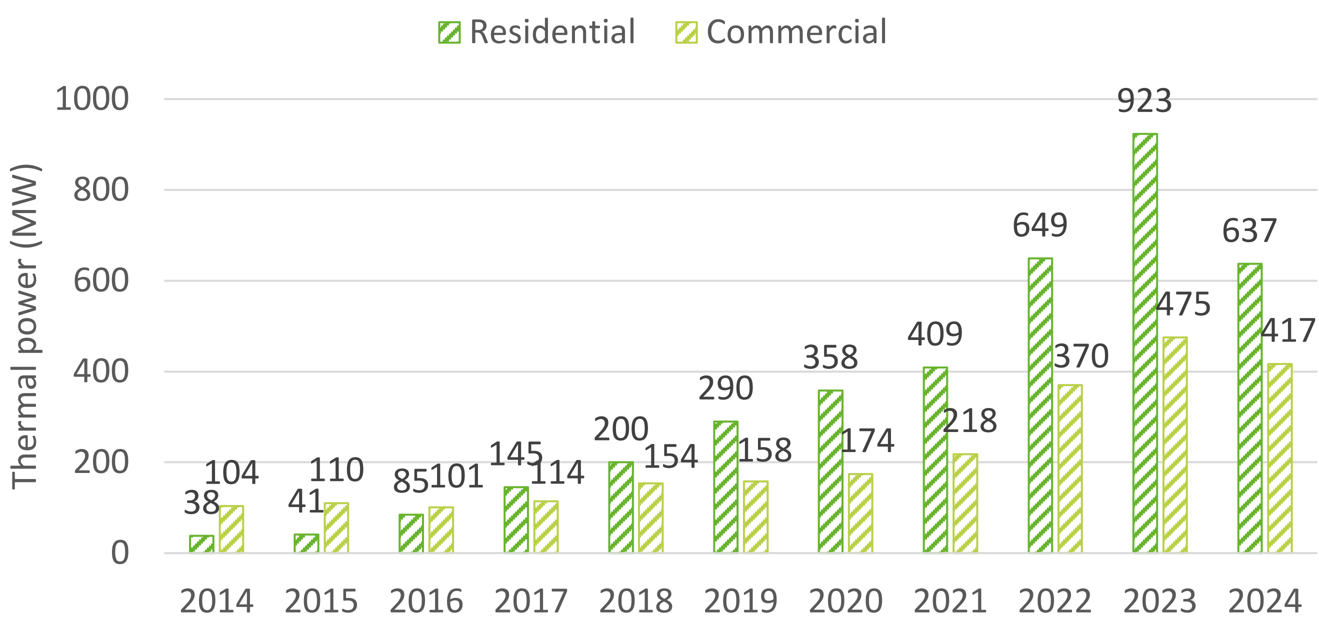


Figure 3: Annual added capacity of heat pumps in the Netherlands (Source: Nationaal Warmtepomp Trendrapport 24/25, DNE Research)

Air Conditioners

Contrary to heat pumps, Figure 4 shows that the air conditioners' market has remained at a similar level since 2020. Until 2019, the sales of air conditioners in the Netherlands were very limited, slowly growing to 121.000 in 2019. However, there has been a sudden increase in sales of more than 250.000 units per year since 2020. This was most probably triggered by a period of a couple of heat waves, but the continuation of this phenomenon is also in relation to the high share of solar energy in Dutch power demand (18% in 2024) [5] and the fact that due to local congestion, the owners of PV systems faced curtailments, especially during the summer period. Since the demand for cooling coincides with the peak of power generation from solar panels, which can't all be delivered to the grid, many people decided to invest in air conditioners and use their own electricity for cooling. Consequently, these homes are now also equipped with a system that can provide them with heat during the winter period. Depending on their needs, this can mean a partial, but also possibly complete coverage of heat demand, especially in homes where bedrooms are not being heated. In 2024, the sales of air conditioners reached 268.000 units.

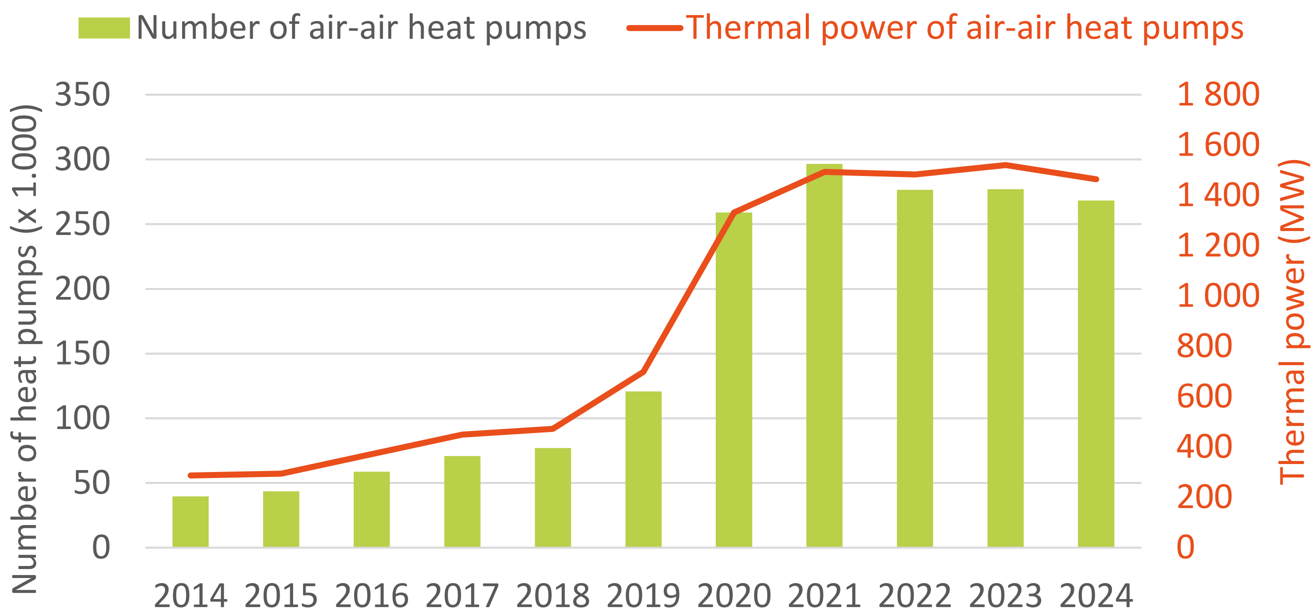


Figure 4: Annual sales of air conditioners in the Netherlands (Source: Nationaal Warmtepomp Trendrapport 24/25, DNE Research)

Economic Figures

As expected, since the sales of heat pumps in the Netherlands decreased by 30% in 2024, the imports, shown in Figure 5 have also decreased by a similar ballpark figure of 34%, reaching the value of 231 million EUR. Leading importing countries were South Korea, China, and Sweden, together covering 53% of the imports. It is also interesting to note that the imports of heat pumps from other EU countries covered 60% of Dutch imports (139 million EUR).

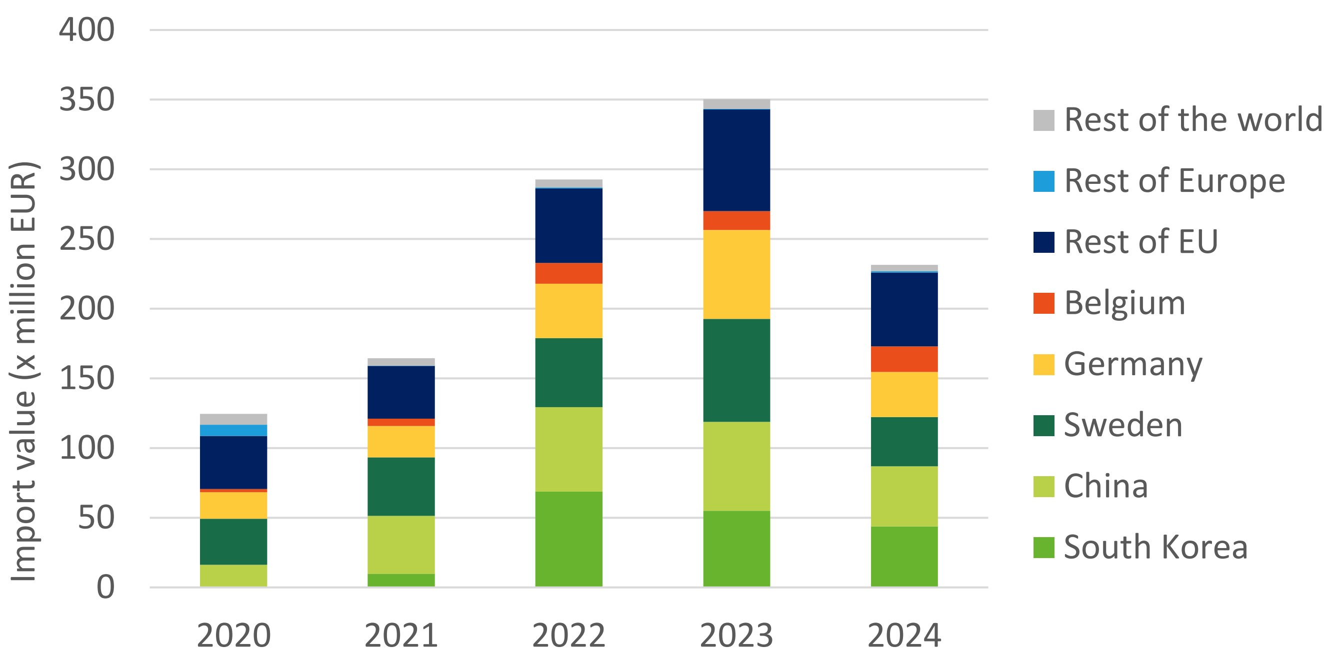


Figure 5: Imports of heat pumps to the Netherlands (Source: Primary Access DNE Dashboard)

Figure 6 presents the exports of heat pumps from the Netherlands, covering 37% of imports (86,2 million EUR in 2024). The decrease in exports by 40% clearly indicates that the Dutch heat pumps sector didn't manage to cover the losses in the domestic market by exporting to other markets, neither in nor outside Europe. The largest exporting markets were Germany, Belgium, and the UK, covering 55,1 million EUR or 64% of exports. And the exports to the common EU market were at the level of 73,8 million EUR, covering 86% of all exports of heat pumps from the Netherlands.

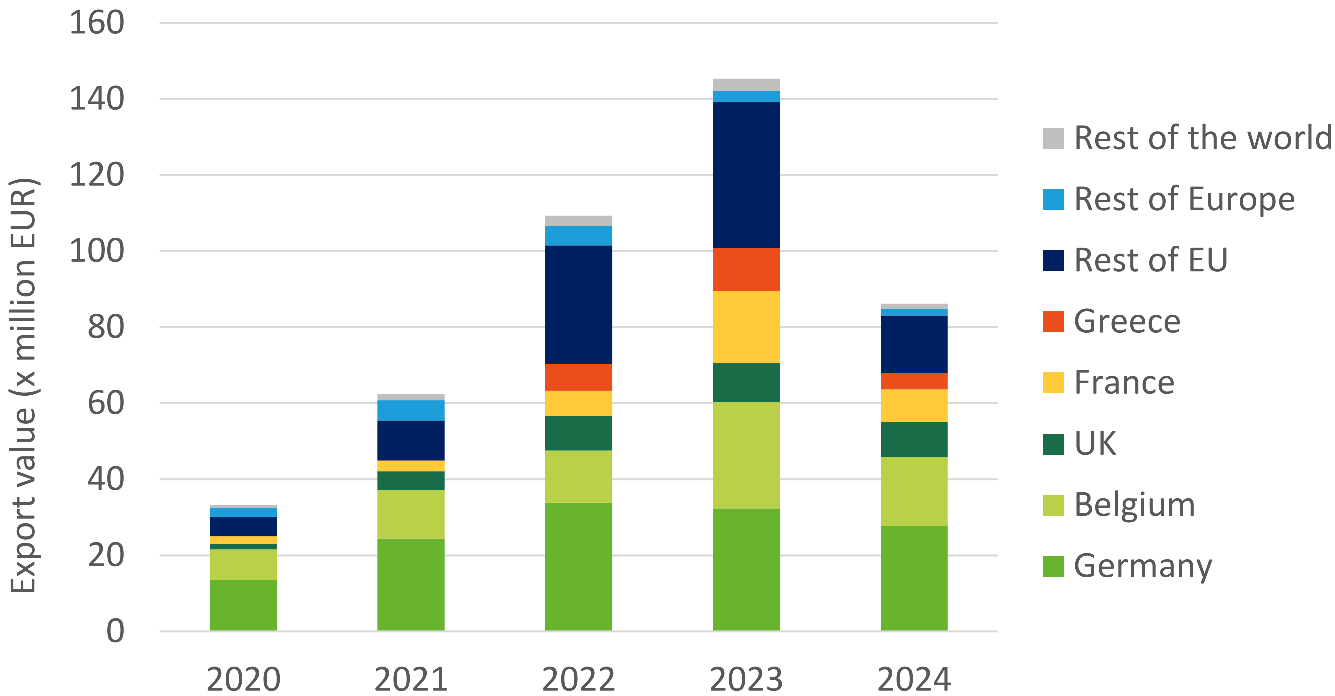


Figure 6: Exports of heat pumps from the Netherlands (Source: Primary Access DNE Dashboard)

Bumpy Ride For Heat Pumps

When examining the reasons for the decrease in sales of heat pumps in 2024, one needs to take into account that the market partly behaved in line with many other markets Europe-wide, as shown in the analysis of imports and exports. But the heat pump sector in the Netherlands also faced changes in energy policy, which had an additional direct impact, as presented in Figure 7. Compared to 2021, in 2022 and 2023, there was an annual increase of sales of heat pumps at the level of 50.000 per year. The announcement in 2022 of a ban on sales of gas boilers from 2026 resulted in a decrease in sales of gas boilers by around 100.000 in 2023. But the new government cancelled the decision to ban the sale of gas boilers and also announced the plan to stop the net metering in 2027. This resulted in a decrease of sales of heat pumps by 50.000 and an increase of sales of gas boilers by almost 100.000, bringing to increase of sales of all heating devices by 50.000 in 2024. The additional increase in sales of gas boilers could be explained by the fear of inconsistencies in energy policy. The sales of air conditioners remained at a similar level during the observed period.

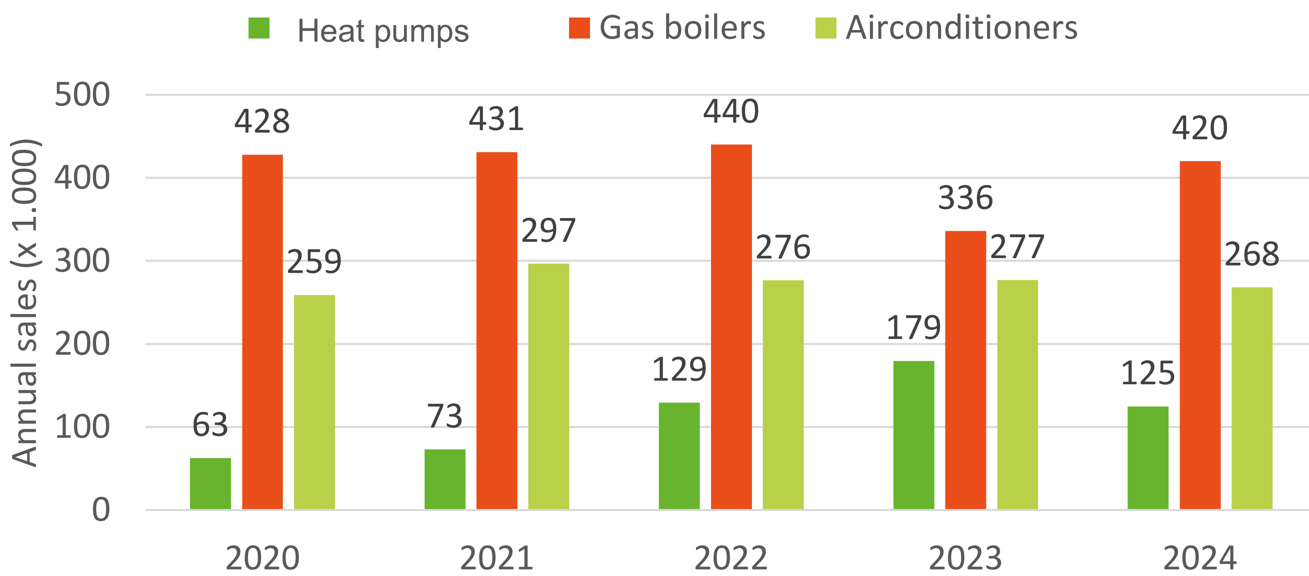


Figure 7: Inter-relation of sales of different heating devices in the Netherlands (Source: Nationaal Warmtepomp Trendrapport 24/25, DNE Research)

Dutch Electricity Grid Capacity a Prerequisite

Virtually all global regions are increasing renewable electricity production and are expanding electrification at the expense of fossil fuels' use. In the Netherlands, the electricity grid capacity in existing dwellings' districts is limited to 1,5-2 kW average simultaneously because of the country's own historical natural gas stocks. Currently, the national electricity grid's capacity has started to be a limiting factor for increasing the deployment of heat pumps. Whilst the TSO's and DSO's plan to expand gradually the electricity grid's capacity over the next decade, the sector is challenged to enable heat pumps' flexible electricity demand to help shift demand peaks in order to reduce grid congestion as part of a public-private National Action Plan. One reason why hybrid heat pumps – a combined gas-boiler and an air-water heat pump - have a relatively large share of over 60% of all heat pumps in residential renovations in the past two years, as shown in Figure 8, overall, hybrid heat pumps comprise some 38% of annual sales of heat pumps.

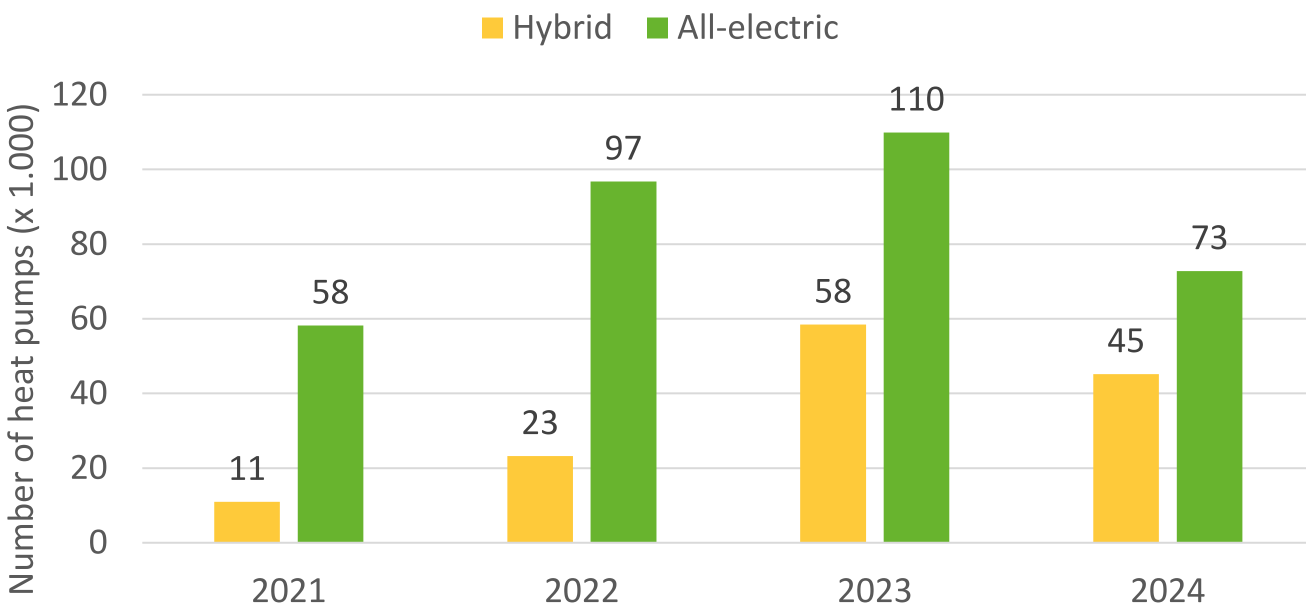


Figure 8: Annual sales of residential heat pumps in the Netherlands by energy source (Source: Nationaal Warmtepomp Trendrapport 24/25, DNE Research)

Outlook

At the end of the year 2024, some 1 in 12 dwellings in the Netherlands were equipped with a heat pump. The Dutch infrastructure and sector are excellently positioned to expand the installed heat pumps' base to meet the 1 in 5 target in 2030. Air-sourced heat pumps are a global default option. Dutch sub-soil is particularly suitable for shallow geothermal-sourced heat pumps. And the (natural) gas grid provides for hybrid heat pumps as a no-regret intermediate step for many building owners. Current market development trends are, however, insufficient to meet that target, so a step up is required, demanding consequent public policies and policy instruments in addition to the sector's commitment and ambition. If current trends in the sales of heat pumps in the Netherlands continue, it is expected that the sales of heat pumps will remain at the level of 120 thousand heat pumps per year until 2030. Still, in order to satisfy the target of the Dutch government of 1 million installed (hybrid) heat pumps in existing dwellings by 2030, the sales should increase more than 3 times by 2030. The national public-private action plan for residential heat pumps 2025-2030 facilitates further market growth and heat pumps' flexibility in the current capacity-limited electricity grid.

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