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Technology Collaboration Programme on Heat Pumping Technologies (HPT)

Annex 54

Heat Pump Systems with Low-GWP Refrigerants

Final Report

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Preface

This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, IEA.

The IEA

The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the implementing agreement for a programme of research, development, demonstration and promotion of heat pumping technologies. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the TCP, collaborative tasks, or “Annexes”, in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.
The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

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The HPT TCP is part of a network of autonomous collaborative partnerships focused on a wide range of energy technologies known as Technology Collaboration Programmes or TCPs. The TCPs are organised under the auspices of the International Energy Agency (IEA), but the TCPs are functionally and legally autonomous. Views, findings and publications of the HPT TCP do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

The Heat Pump Centre

A central role within the HPT TCP is played by the Heat Pump Centre (HPC).

Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimise the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology including researchers, engineers, manufacturers, installers, equipment users, and energy policy makers in utilities, government offices and other organisations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:
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Foreword

The HVAC&R industry's shift to low-GWP refrigerants is driven by the need to mitigate global warming and adhere to international agreements such as the Kigali Amendment to the Montreal Protocol. Annex 54: Heat pump systems with low-GWP refrigerants started in 2019, aiming at promoting the application of low-GWP refrigerants to accelerate the phase-down of high-GWP HFCs and developing design guidelines for optimized components systems for low-GWP refrigerants. Member countries are Austria, France, Germany, Italy, Japan, Korea, Sweden, and the USA. Participating organizations are shown in Figure 1. This executive summary highlights work conducted, including reviews of the latest developments in low-GWP refrigerants, case studies for optimizing components and systems, and 2030 outlooks.

Figure 1: Annex 54 participants

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1. Executive Summary

The HVAC&R industry's shift to low-GWP refrigerants is driven by the need to mitigate global warming and adhere to international agreements such as the Kigali Amendment to the Montreal Protocol. Annex 54: Heat pump systems with low-GWP refrigerants started in 2019, aiming at promoting the application of low-GWP refrigerants to accelerate the phase-down of high-GWP HFCs and developing design guidelines for optimized components systems for low-GWP refrigerants. Member countries are Austria, France, Germany, Italy, Japan, Korea, Sweden, and the USA. Participating organizations are shown in Figure 1. This executive summary highlights work conducted, including reviews of the latest developments in low-GWP refrigerants, case studies for optimizing components and systems, and 2030 outlooks.

Figure 1: Annex 54 participants

Key Findings:

- **State-of-the-Art Technologies**: While A1 refrigerants are limited, CO_2 is expanded in the commercial refrigeration application. A2L refrigerants, particularly R-32 and its mixtures, are widely researched. A3 refrigerants are widely investigated, especially in Europe, and considered for systems with low charges due to safety concerns.
- **Standards and Policies**: The Kigali Amendment, the EU F-gas regulations, and the USA AIM Act drive the regulatory landscape, promoting low-GWP refrigerants and updating safety standards.
- **Case Studies and Design Guidelines:** R-516A shows significant promise as a low-GWP alternative to R-134a, offering comparable performance with reduced direct emissions. Studies on refrigerants like R-290, R-32, R-454B, R-452B, and R-466A indicate their potential as replacements for R-410A. System design guidelines stress the importance of enhancing system efficiency, ensuring safety, and meeting regulatory standards through optimized component designs, which are crucial for achieving both environmental sustainability and operational excellence.
- **Design Optimization**: Optimization frameworks, such as Genetic Algorithms for heat exchangers, show significant improvements. Comprehensive Life Cycle Climate Performance (LCCP)assessments highlight the impact of system efficiency and refrigerant leakage on emissions. Among R-410A replacements, R-290 demonstrates the lowest LCCP.
- **Outlook for 2030**: Continued research into A1 refrigerants, in-depth safety studies on A2L and A3 refrigerants, and exploration of near zero-GWP refrigerants are crucial for future advancements.

2. Review of State-of-the-Art Technologies

The ***U.S.*** intends to provide the most updated and comprehensive review of advancements of low GWP alternatives for R-410A in residential air conditioning applications from research and regulation perspectives. CO_2 (R-744) with a low GWP around 1 requires significant system design changes due to its low critical temperature and high operating pressure. However, the CO_2 system has expanded in commercial refrigeration applications. R-466A, recently proposed as a promising R-410A alternative, is non-flammable and has a lower GWP but requires comprehensive evaluation to establish its efficacy and safety. A2L refrigerants, including R-32 and R-454B, are widely studied for their favorable thermodynamic properties and are used in many blends aimed at reducing GWP while maintaining performance. Current components and system designs are also evolving to accommodate low-GWP refrigerants. Advanced heat exchanger designs using non-round, shape-optimized tubes are being developed to enhance efficiency, with significant performance improvements achieved through the integration of Approximation-Assisted Optimization (AAO) with Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA). Additionally, design modifications and optimizations in compressors and expansion valves are necessary to enhance compatibility and performance with low-GWP refrigerants, focusing on efficiency, reliability, and reduced environmental impact. Thermophysical properties and heat transfer characteristics are essential in selecting optimal refrigerant candidates. The report provides a detailed thermodynamic analysis of refrigerants such as R-123, R-134a, R-245fa, R-404A, and R-410A, comparing performance metrics, including efficiency and environmental impact, across various applications. Comprehensive safety research focuses on understanding the flammability risks of A2L and A3 refrigerants, with updated safety standards and risk assessments essential to facilitate the safe adoption of these refrigerants in HVAC&R systems.

Sweden has long been a pioneer in the research and development of natural refrigerants, with over two decades of intensive study dedicated to reducing the environmental impact of HVAC systems. Swedish research emphasizes the importance of minimizing refrigerant charges to enhance safety and efficiency. This approach aligns with stringent EU regulations and the Kigali Amendment, which mandate the phasedown of high-GWP refrigerants. Innovative technologies in Sweden include the development of compact heat exchangers and advanced compressor designs that effectively minimize refrigerant charges without compromising performance. Sweden's dedication to environmental sustainability is evident in its continuous efforts to advance technologies that utilize low-GWP refrigerants such as hydrocarbons, CO_2, and ammonia, thereby significantly reducing the environmental footprint of HVAC systems. Sweden's innovative approaches include using flattened tubes in heat exchangers, which provide the same heat transfer surface as circular tubes but with significantly reduced internal volume, enhancing both efficiency and reducing the refrigerant charge. Additionally, Swedish researchers are pioneering compact compressors with minimal oil content, which is crucial for further reducing the refrigerant charge. These advancements reflect Sweden's commitment to integrating sustainable practices into HVAC technology, pushing the boundaries of what is possible in terms of environmental performance.

The ***Italian*** research community, comprising institutions like the National Research Council, the Polytechnic of Milano, and the University of Padova, has been actively exploring low-GWP refrigerants. These efforts focus on assessing the thermophysical properties of new refrigerants, evaluating performance during flow boiling and condensation, and analysing energy performance in lab environments. Notable low-GWP refrigerants studied include R-32 and R-290, which have shown promising results in efficiency and environmental impact compared to high-GWP refrigerants like R-410A. Below is a summary of Italy's activities regarding using low-GWP refrigerants in heat pumping systems. The Italian research team comprises three research institutes (National Research Council, Polytechnic of Milano, University of Padova) actively involved in numerous research projects about low-GWP refrigerants complementary to each other. The research activities span from fundamental studies, which typically focus on components, to applied studies, which are usually carried out at the system level, and may be listed as follows:

- Assessment of refrigerant thermophysical properties.
- Assessment of performance during flow boiling and/or condensation, namely heat transfer coefficient and pressure drop.
- Assessment of energy performance, namely heating capacity and Coefficient of Performance (COP) in drop-in application in the laboratory environment.
- Energy and environmental analysis of traditional and innovative heat pump configurations that rely on low-GWP refrigerants, either with pilot plant monitoring or yearly simulation.

The main findings of the full set of research activities may be summarized as follows:

- In the ongoing EU ECHO project, low-GWP refrigerants will be considered a viable alternative to standard refrigerants for working fluids in a single-stage heat pump integrated into an innovative thermal storage system.
- There is a tendency to progressively reduce the diameter of channels used in heat exchangers to lower the refrigerant charge inside heat pumps. To assess and develop condensation and flow boiling heat transfer correlations, wide databases must be collected encompassing conditions that include pure fluids, mixtures, and small diameter channels. Heat transfer coefficients have been measured inside 1 mm and 3.4 mm diameter channels with binary mixtures composed of HFOs (hydrofluoroolefins) and HFCs (hydrofluorocarbon). Flow boiling experiments have been performed with ternary mixtures R-455A and R-452B.
- R-32 and R-290 are the most viable options for small-medium capacity heat pumps. Their use typically leads to energy performance that is similar, or even better, than that achieved with the "old" standard refrigerant for this application, i.e., high-GWP R-410A. From the environmental perspective, simulation results revealed that using the two above-mentioned alternative refrigerants is beneficial as the TEWI reduces with respect to baseline systems.
- The same refrigerants are considered for the replacement of R-134a in heat pump water heaters with the same abovementioned advantages. From the safety concern point-of-view, it is proved that heat pump water heaters can be manufactured with a charge below the maximum allowable threshold value set by standards (i.e., 152 g for R-290 and 1842 g for R-32).
- For medium-large capacity heat pumps, which are typically operated with R-134a, many low-GWP refrigerants can be used as alternatives. Broad-range drop-in tests in the laboratory facility revealed that R-513A is the refrigerant that provides the most similar heating capacity while leading to some penalization in terms of COP, whereas R-1234ze(E) is the refrigerant that shows the most similar COP but suffers from the largest capacity reduction. Overall, R-513A seems a good option for medium-capacity heat pumps with a positive displacement compressor. In contrast, R-1234ze(E) seems the preferred choice in medium to large systems manufactured with centrifugal compressors.
- The real performance of two geothermal heat pumps working alternative refrigerants has been measured in a pilot facility within the concluded EU GEO4CIVHIC project. In particular, R-454B, a mixture of synthetic refrigerants (R-32 and R-1234yf) and isobutane (R-600a, hydrocarbon), proved to be efficient for medium-temperature residential heat pumps. These two refrigerants had been chosen based on computer simulations on a wider range of boundary conditions, resulting in the best COP values among mid-term, R-454B, and long-term, R-600a, refrigerants.
- The use of natural fluids, such as CO_2, is increasingly growing. A dual-source transcritical CO_2 heat pump that uses hybrid photovoltaic-thermal (PV-T) collectors as evaporators has been studied. The heat pump works in different modes using air or solar radiation as thermal sources.
- The combined use of air and ground as heat sources can be a strategy to improve the efficiency of heat pumps at lower costs because the length of the borehole heat exchangers can be reduced. A heat pump prototype working with R-32 has been investigated.

In ***France***, the HVAC&R industry's evolution is profoundly influenced by international environmental agreements such as the Montreal Protocol and the Kigali Amendment, which mandate a transition towards low-GWP refrigerants. French research has been pivotal in exploring the potential of various fourth-generation refrigerants, including HFOs (Hydrofluoroolefins) and natural refrigerants like hydrocarbons and CO_2. Significant advancements have been made in understanding the thermodynamic properties and efficiency of these refrigerants. For example, research has demonstrated that CO_2, despite its high operating pressure and low critical temperature, can be effectively utilized in heat pumps and refrigeration systems through innovative system designs. The adoption of refrigerants like R-454B and R-1234ze(E) is becoming more widespread due to their lower environmental impact and favorable performance characteristics.

In ***Germany***, due to the nature of the new F gas regulation for residential applications, the share of low-GWP non-halogenated refrigerants started to become visible, particularly pushing air-to-water heat pumps into the German market. On the market of eligible heat pumps, this heat pump type charged with R-290 got a share of about 30%. The high share of air-to-water heat pumps in Germany led to an overall share of R-290 as refrigerant of about 20% (Figure). In comparison, R-32 got a share of about 30%, which mainly corresponds to split heat pumps. In the last years, the R-32 share increased, yielding the absolute dominance of R-32 in this type of appliance and the improved eligibility of air-based heat pumps for a few years, see Figure . Today, it is important to understand that this market of eligible heat pumps mainly targets single-family houses. Therefore, further development in the share of refrigerants can be expected.

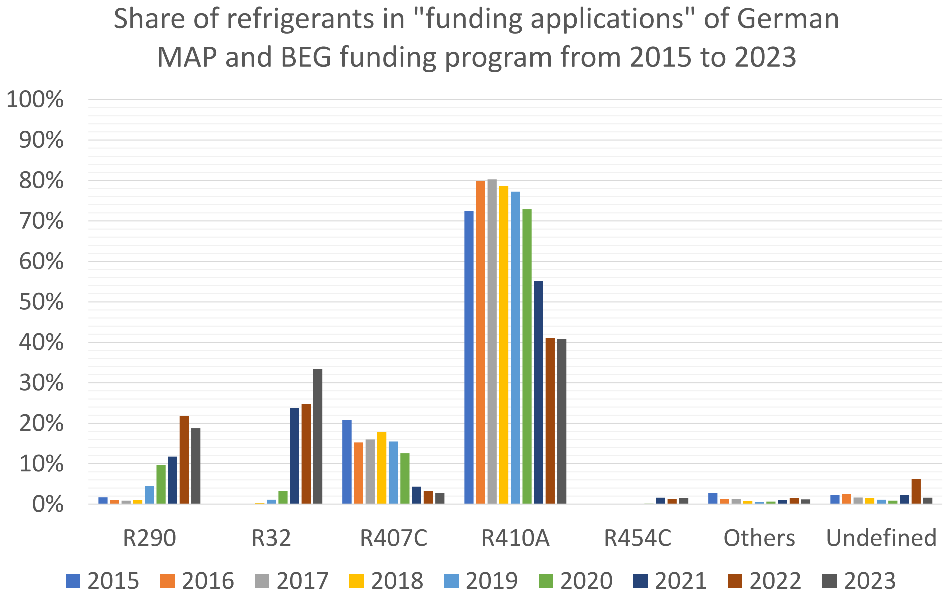

Figure 2: Refrigerants used between 2016 and 2023 in funded heat pump applications.

Even though global and national legal frameworks staked out the pillars for these changes in years ahead, major obstacles still hindered an earlier change. Among others, these obstacles were major reasons why this transition hadn't started earlier:

- a lack of available components,
- safety issues,
- the need to adapt national regulations like building codes,
- an urgent need to train installers,
- increasing the expertise of R&D engineers of the heat pump manufacturers and
- especially an improved economic incentive to prefer a heat pump to alternative heating systems.

It should be noted that the transition still happens mainly for single-family houses, which represent a share of less than 50% of heating systems in Germany when considering multi-family houses and district-heated buildings. The transition to heat pumps with low-GWP refrigerant has not started for indoor-installed heating systems. It is part of current research and development (except for hot water heat pumps, mainly R-290 and partially R-1234ze(E) are used). Markets for heat pumps in multi-family houses are still small and lack, in general, a transition away from fossil fuels-operated heating systems to heat pumps. Since the spectrum of available components and the speed of newly introduced components has increased drastically, it can be presumed that most houses will see a direct shift to heat pumps with low-GWP refrigerants in the next years.

The ***Korean*** HVAC&R industry actively embraces low-GWP refrigerants driven by environmental concerns and regulatory mandates. The shift towards refrigerants like R-32, which offers a lower GWP than traditional refrigerants like R-410A, is a significant focus. R-32 is more environmentally friendly and boasts superior performance metrics, such as higher energy efficiency and reduced refrigerant charge requirements. Korean research has been extensive, covering the thermodynamic properties, energy efficiency, and performance characteristics of R-32 in various air conditioning systems, including window, wall-mounted, and ceiling-mounted units.

3. Standards and Policies

The regulatory landscape is crucial in driving the adoption of low-GWP refrigerants. International agreements such as the Montreal Protocol and Kigali Amendment mandate the phasedown of high-GWP refrigerants, promoting global efforts towards adopting low-GWP alternatives. The EU F-gas regulations have implemented stringent measures to reduce emissions from high-GWP F-gases, and the US EPA SNAP program evaluates and approves low-GWP refrigerants for specific applications, with restrictions on flammable refrigerants to ensure safety.

In Europe, a quest for environmentally friendly refrigerants began around 20 years ago because of the introduction of EU Regulation No. 40/2006 and 517/2014 on fluorinated greenhouse gases and the Kigali amendment to the Montreal protocol. The recent release of the updated version of F-Gas regulation (EU Regulation 573/2024) has introduced a clear direction towards using ultra-low GWP refrigerants, which, in some applications, set a threshold value for GWP equal to 150. Consequently, many ongoing research and development activities deal with this topic. The transition from HFC refrigerants to higher shares of low-GWP refrigerants is an ongoing hot topic in the heat pump market. In addition, with the introduction of a new F-gas Regulation in 2024, this transition heavily accelerated in all heat pump device classes.

The new European F-gas regulation and the international Kigali amendment to the Montreal protocol will force a phase-out (in Europe) or phase-down (internationally) of HFC refrigerants. Natural refrigerants like hydrocarbons, carbon dioxide, and ammonia can and will take over the largest market share for all types of products, with few exceptions. Synthetic HFO refrigerants may keep some niche markets. HFOs are low-GWP but are flammable and may be restricted as they are, with some exceptions, PFAS substances, which have possible negative effects on the environment and human health. Presently, a total ban on PFAS substances is proposed in the EU.

Due to climate change, most countries have promised to be climate-neutral by the middle of the century. This means a complete phase-out of fossil fuels. As biofuels will be insufficient as substitutes, the new energy system will be based on renewables and nuclear, all delivering energy in the form of electricity. Therefore, we will head towards an energy system based on electricity. Electrification of the heating sector will require a transition to heating by heat pumps, directly or indirectly, through district heating. Low GWP natural refrigerants will be required in large quantities in this transition. The increased demand for cooling will also contribute. Some countries, primarily Scandinavian, have already come very far in this transition towards heat pumps, and the change to natural fluids will then happen as older heat pumps are replaced. Other countries will move directly to heat pumps with natural fluids.

4. Case Studies and Design Guidelines

We investigated many case studies and design guidelines aimed at optimizing components and systems for low-GWP refrigerants. The focus is on practical implementations and performance evaluations to guide industry adoption.

The ***U.S.*** has conducted extensive case studies to explore the practical applications and performance of low-GWP refrigerants. The case studies include R-516A in heat pump systems, which shows promise as a low-GWP alternative offering comparable performance to R-134a in both cooling and heating modes, with significant reductions in direct emissions. Studies on unitary air-conditioning systems using refrigerants like R-290, R-32, R-454B, R-452B, and R-466A highlight their potential as replacements for R-410A, with R-290 demonstrating the lowest LCCP. Design guidelines for optimization recommend using small diameter tubes and advanced simulation tools like ISHED to improve heat exchanger efficiency and reduce environmental impact. Additionally, system design guidelines emphasize enhancing system efficiency, ensuring safety, and meeting regulatory standards through optimized component designs.

The ***Swedish*** work consists of several projects performed during the last few years. The complete country reports are thus compilations of results presented in other reports. Most of the projects have been funded by the Swedish Energy Agency or by the EU and have been performed by either of two research groups: The Division of Applied Thermodynamics and Refrigeration, Department of Energy Technology, KTH, and/or a branch of RISE Research Institutes of Sweden. Research on natural refrigerants has been ongoing in Sweden for over 20 years. Throughout this time, several conclusions have been drawn concerning the use of these refrigerants, and some of the older projects have been summarized in the first part of the country report, along with results from recent studies. Generally, it is concluded that a low charge of refrigerant should always be an important design goal for any heat pump, independent of the type of refrigerant. Low GWP refrigerants are almost always flammable, and low-refrigerant charges reduce the risks. Because of possible leakages, the charge of refrigerant in the systems should be minimized, especially if they are to be located indoors. Synthetic refrigerants with low or high GWP have environmental effects, and the charge should be reduced for this reason. It should be clear that low charges can and should be realized without compromising efficiency. As HFC fluids have been considered safe and their environmental effects have only recently been known or considered, the volume of the systems and the mass of refrigerant have not been a concern in the design. Re-thinking the designs to reduce charge is, therefore, to some extent, easy. This can be achieved by carefully selecting the components and the system design. As a basic example, a circular tube will have a much larger internal volume than the tube after flattening. Both will have the same heat transfer surface area, but the flattened tube will probably have less volume and better heat transfer performance. Investigations have shown the distribution of charge between the components of the system. A large share of the charge may be in the compressor using compact heat exchangers, e.g., braced plate heat exchangers and short liquid lines. With hydrocarbons, much refrigerant will be absorbed into the compressor oil. Decreasing the oil content and using oils with lower miscibility is important in future low-charge systems. Compressors with less oil should be developed, and the selection of oils should prioritize oils with low solubility. As a large share of the charge of hydrocarbons may be solved in the compressor oil and cannot easily be released, the standards should allow taking this into account when calculating the allowable charge. In lab tests, prototype water-to-water systems with about 10 g of hydrocarbon per kW of heating capacity have been demonstrated. Components or solutions from the automotive industry (flat aluminum multi-port tubes, compact compressors) could be an inspiration for future development. In one project, a prototype of a domestic water-to-water heat pump (8 kW) was built using ammonia as refrigerant. The system required about 120 g of charge when using prototype heat exchangers with multichannel aluminum tubes. A difficulty with ammonia is finding suitable components for small-capacity systems that are commercially available. To our best knowledge, there are no hermetic ammonia compressors in sizes suitable for domestic systems. Research projects related to charge reduction have continued during the course of the Annex. Within the project, Eco Pack, a heat pump prototype using isobutane, was shown to operate well and have heating capacities of up to 12 kW with only 120 g of refrigerant. The project ProPack aimed to demonstrate a split AC system, air-to-air, with a charge of 150 g of propane. This goal was not quite reached, but the project still demonstrated that the goal may be within reach in the future. The project revealed that reducing charge in air/refrigerant heat exchangers is more challenging than in liquid/refrigerant heat exchangers and that the headers' design is an important challenge. An additional challenge is the long lines connecting the outside and indoor parts of the split system. Ideally, the system should be designed so that these lines mainly have gas.

A study on 3-D printed heat exchangers has been initiated to decrease the volume of heat exchangers. This technology may have advantages in the future but is still too expensive for most heat pump or refrigeration applications.

The Swedish market survey about the use of refrigerants and the heat pump market now and in the future was conducted during the first part of 2023 when the heat pump market was booming. Some conclusions from this survey are that:

- The demand for heat pumps is expected to be high or very high in the coming three years.
- Prices of heat pumps are expected to increase.
- The market is still dominated by products with synthetic refrigerants, with propane having a market share of 2-3%, except in exhaust air heat pumps, where propane's market share is estimated to be 34%.
- HFO-blends are only used for liquid/water heat pumps; the share is estimated to be 7% of the installations done in 2023.
- High GWP refrigerants (R-410A and R-407C) are still used to a large extent.
- The installed heat pumps are mainly replacing old heat pumps, as gas/oil heaters are quite rare in Sweden today.

In another study, six heat pump manufacturers and four importers were asked to respond to a survey concerning their plans for choosing refrigerants in their future products. This study revealed that most respondents were expecting to see flammable refrigerants being used in the future. Training of technicians was considered an obstacle in this transition.

CO_2 systems are now the normal solution for supermarket refrigeration in Sweden. Research in this area focuses on combining these systems with heat recovery for heating (of buildings and domestic hot water), air conditioning, thermal energy storage, etc.

The risks connected to the use of low GWP synthetic fluids and their stability are investigated in another research project. Polymerization of HFOs causing the formation of polymer foams has been reported, but the necessary conditions still need to be well known. Studies of refrigerant degradation and possible changes in concentrations in refrigerant mixtures have also been initiated, but no important findings have been reported yet.

In conclusion, in ***Sweden*** and the rest of Europe, the new F-gas directive and the proposed total ban of all PFAS fluids are rapidly driving the development towards using natural refrigerants such as hydrocarbons and carbon dioxide for supermarket refrigeration. Contacts with manufacturers, installers, and importers through interviews and questionnaires have shown that the industry in Sweden is prepared for the transition but that only a few new domestic products with hydrocarbons are on the market yet, except for exhaust air heat pumps where propane has been common since many years. For multi-family buildings and industries/offices, hydrocarbon heat pumps are marketed by several Swedish companies, and some of them include novel solutions to maintain high safety levels. Some examples of such installations and the novelties in the designs are also given in the report.

CETIAT's study in ***France*** assessed the performance of low-GWP refrigerants R-410A, R-454B, and R-32 in finned tube heat exchangers, finding that R-454B could replace R-410A without design changes, while R-32 required optimization. Another study evaluated alternative refrigerants like R-459A, R-454B, R-447A, HPR-2A, and R-32 for R-410A replacements in a 10 kW Air-to-Water heat pump, and R-1234yf, R-513A, and R-450A for R-134a in a Heat Pump Water Heater, with R-454C and R-455A tested for R-407C in a 3 kW Water-to-Air heat pump, highlighting R-454B and R-459A's superior performance. Additionally, a project developed a 5 kW R-290 heat pump prototype, achieving minimal refrigerant charges of 190 g and 90 g through optimizations such as reduced superheat and a semi-hermetic automotive compressor. These studies underscore the feasibility and efficiency of low-GWP refrigerants in residential heat pumps, providing valuable insights and guidelines for eco-friendly system designs in compliance with international regulations.

In the second study proposed in France, five alternative refrigerants, R-459A, R-454B, R-447A, HPR-2A, and R-32, were investigated for the replacement of R-410A in a 10 kW Air-to-Water (A/W) reversible heat pump. Three alternative refrigerants for R-134a, R-1234yf, R-513A, and R-450A, were tested in a split Heat Pump Water Heater (HPWH) having a water tank of 200 liters. R-454C and R-455A were evaluated as a possible alternative to R-407C in a 3 kW Water-to-Air (W/A) reversible heat pump. A total of 10 alternative refrigerants with low GWP were evaluated with not less than 130 performance tests. These experimental results will be useful for the HVAC community by facilitating the selection of the most promising candidates for the replacement of R-410A, R-134a, and R-407C in residential heat pumps.

R-459A, R-454B, R-447A, HPR-2A, and R-32 were investigated for the drop-in replacement of R-410A in a 10 kW air-to-water reversible heat pump. R-410A replacement by HFC/HFO mixtures showed no problem, and the performance obtained is, aside from some very few exceptions, almost equivalent (+/- 10 %) to that with R-410A. Furthermore, the heat pump worked normally with alternative refrigerants (HFC/HFO mixtures) in operating-limit conditions. With R-32, the operating map of the heat pump would be decreased because of the high discharge temperatures reached. R-454B and R-459A showed the best performances.

R-454C and R-455A were evaluated as possible alternatives to R-407C in a 3 kW water-to-air reversible heat pump. The R-404C seems more suited to replacing the R-407C for a reversible machine since the performance is almost equivalent to that of the R-407C in both operating modes. For the heating-only mode, R-455A achieves the best results (+ 6.1 % to + 8.6 % heating capacities and equivalent COP). R-454C and R-455A can therefore be considered as alternatives for R-407C.

R-1234yf, R-513A, and R-450A were tested for replacing R-134a in a split heat pump water heater with a water tank of 200 liters. They showed equivalent performances to R-134a. The discharge temperatures reached with alternatives are lower than those with R-134a, of -14 K for R-450A, -10 K for R-1234yf, and -5 K for R-513A. R-513A and R-1234yf might be considered as alternatives to R-134a without significant performance impact, and R-450A might be considered as alternatives to R-134a, but with a decrease in the thermal capacity of the system (longer heating up time). Except for R-450A and R-513A, which belong to the A1 ASHRAE safety class, all other alternatives, R-1234yf, R-459A, R-454B, R-447A, HPR-2A, R-32, R-454C, and R-455A, belong to an A2L safety class. It means that a new risk must be handled: flammability. Using these alternative refrigerants will require a complete study of the risks, sizing, and compatibility. Figure 3 shows the most promising Low-GWP refrigerants to replace the HFC commonly used in heat pumps.

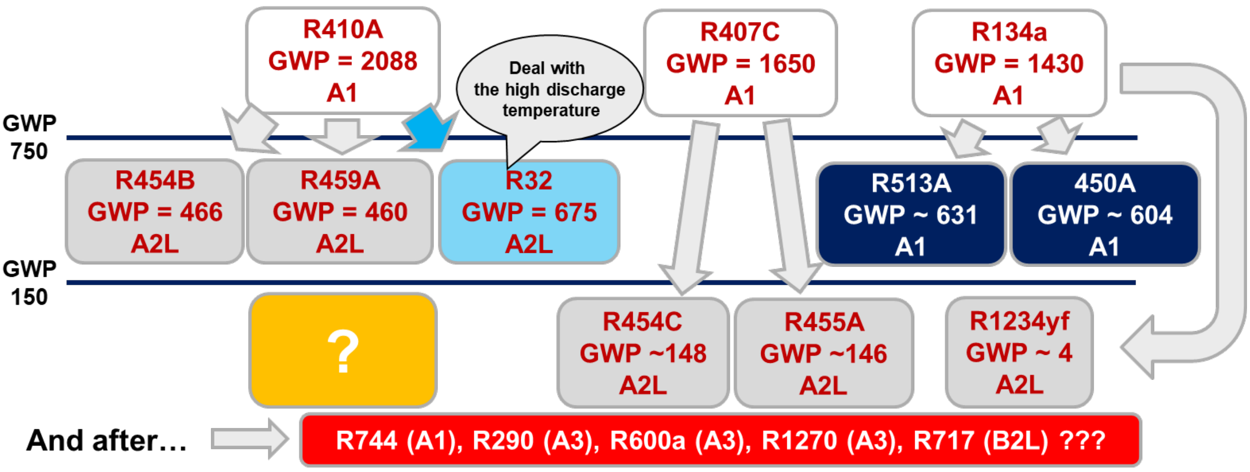

Figure 3: Most promising Low-GWP refrigerants summarized from review work

Long-term alternatives (GWP<150) exist for R-407C and R-134a, but for R-410A, only transition alternatives are available (150 < GWP < 750). Other solutions need to be studied, especially natural fluids. These experimental results were useful to the HVAC community in selecting the most promising refrigerant candidates to replace R-410A, R-134a, and R-407C. Beyond drop-in, improving the thermal performances of the heat pumps would require component optimization. For example, it would be necessary to re-size and replace the expansion valve, especially when a calibrated orifice or a capillary tube is used, or to optimize the design of the heat exchanger(s).

In the third study, replacing HFO with natural flammable fluid requires reducing the refrigerant charge in heat pumps. This third study aimed to develop a heat pump with the minimum amount of propane for an individual 5 kW residential space heating application. An experimental water-to-brine heat pump prototype was built and tested. The unit was designed to be compatible with outdoor air-to-brine heat exchangers. The study first focuses on the influence of gas superheating entering the compressor and compressor speed during charge optimization. It also analyses the influence of different evaporator sizes, condenser sizes, and compressor technologies. Finally, a seasonal performance analysis is performed on two configurations for which the optimal charges are 190 g and 90 g, respectively.

As R-290 has flammable properties (A3 classification), a common safety measure is to reduce the refrigerant charge to its minimum while avoiding negatively impacting performance. In this context, a water-to-water heat pump appears to have the smallest internal volume and, thus, the smallest charge amount. Those units are widely used for ground-sourced applications. However, ground-sourced units require drilling or buried water pipes, which are not available options in every case. That is why the experimental 5 kW heat pump built for this study is a water-to-brine unit compatible with an outdoor air-to-brine heat exchanger. Such a unit can be placed inside a house with a maximum admissible R-290 charge of 150 g.

Numerous technical facets incorporated exhibit a notable impact on charge reduction. Modifying the superheat and downsizing the plate evaporator helps to minimize the optimal charge. Using a semi-hermetic automotive compressor with a minimal oil quantity shows potential. Nonetheless, enhanced modeling encompassing the influence of oil and compressor capacity is imperative for optimizing the energy efficiency of the setup. When a greater capacity is required than can be supplied by max. 150 grams of R-290, one of the safety hazard mitigating measures, is placing a mono block outside the building.

Several R&D activities were reported during the duration of the Annex for ***Germany***. For residential heat pumps, the LC150 project, which started in 2020, is worth mentioning. As a result of more than two decades of European research on charge reduction, this project supported the European heat pump industry in closing the technology gap that still exists for the use of heat pumps with flammable refrigerants like R-290 for indoor applications. Here, two main developments are important for overall charge reduction with acceptable performance. On the one hand, the progress made on the new generation of compressor platforms with less oil discharge reduced inner free volumes in oil sumps. Thus, there was an improved overall oil charge as well as refrigerant-specific improvements for the compression mechanism. On the other hand, progress has been made on an improved two-phase distribution for the overall mass flow range that could occur in a heat pump with speed-controlled compressors and volume-reduced port designs. Both measures taken by the component manufacturers led to about 34 tested combinations of innovative heat exchangers, compressors (several types), and new types of expansion valves that were tested at several thousand operating conditions for optimum charge identification, testing standard rating conditions according to EN 14825 as well as SCOP values according to an agreed testing procedure. As a result, vapor compression circuits – in their designs closely related to ground source heat pumps – with an optimal charge between 124 to 164 g were identified. For a typical rating condition of lower supply temperature, the SCOP range of these systems was between 4.5 and 4.8, with a heating capacity between 8.1 and 12.8 kW. These results do not reflect the highest possible optimum yet since the maximized charge reduction was the focus of the research. Nevertheless, the project consortium believes that these baselines' typical installation rooms (e.g., in basements) will be sufficient to reach out for efficient and safe indoor-mounted R-290 heat pump products in the near future. With small changes in the port design to use it as small liquid receivers, these cycles could even be adapted to be used as secondary systems closer to the functional design of air-to-water heat pumps. This is a typical measure by some manufacturers seen on the European heat pump market to reduce the manufactured refrigeration cycles used within a multitude of heat pump products in their portfolio as a kind of platform strategy. This leads to the topic of "safe design of heat pumps" as another key and core topic for the transition towards low-GWP but flammable refrigerants for a wider spectrum of possible installation locations. In this project and some other projects during the duration of Annex 54, the design of safety zones adjacent to heat pumps was investigated. Only the investigations of outdoor installed heat pumps were finalized during the Annex duration and were reported [1]. For the investigations on indoor appliances, safety zone tests were published elsewhere; see, for example, a publication at the Annual Meeting in 2023 of the German Society of Refrigeration and Air Conditioning [2]. Unfortunately, the testing for safety zones is not covered very well in relevant safety standards like IEC 60335-2-40:2022 or EN 378-1:2016/EN 378-2:2016, neither for outdoor nor indoor appliances. Only recently – at least for indoor appliances – a promising testing routine was proposed for the EN standard as a surrounding concentration test that will lead to a better situation to cope with indoor appliances [3]. Even though numerous manufacturers are now offering R-290 heat pumps with defined safety zones in their installation manuals, the situation in terms of a standardized approach is no better in terms of core safety standards.

By discussion with the industry, many possible configurations were limited to 10 installation scenarios for which heat pump installation locations were simulated in OpenFOAM. For all results, an analysis of isopleth lines and the direct comparison between different configurations were developed to evaluate advantageous installation locations and extract relevant dynamic information for risk assessments.

Korea has conducted a comparative study on the performance of R-32 versus R-410A refrigerants in various types of residential air conditioners, following ISO 5151 and ISO 13253 standards using a psychrometric calorimeter chamber. The analysis indicates that R-32 is a highly promising alternative with its significantly lower Global Warming Potential (GWP) of 675 compared to R-410A. Notably, R-32 performs better and requires a lower refrigerant charge. For window-type air conditioners, several modifications were implemented to adapt to R-32. The compressor's displacement volume was reduced by 3.8%, the oil quantity was decreased by 28.6%, and the refrigerant charging quantity was lowered by 22.5% compared to R-410A systems. Additionally, the inner diameter and length of the capillary tube were minimized due to the lower mass flow rate of R-32. These changes resulted in a cooling capacity and Energy Efficiency Ratio (EER) that were 2% and 6% higher, respectively, than those achieved with R-410A. Moreover, the combined energy efficiency ratio in cooling mode for R-32 systems was 7% higher than that of R-410A systems. Similar adjustments were made to wall-mounted air conditioners. The oil quantity for the R-32 twin rotary compressor was 12.5% lower, and the refrigerant charge was reduced by 26.3%. The Electronic Expansion Valve (EEV) was also modified to accommodate the smaller mass flow rate of R-32. The cooling EER and heating COP were found to be comparable to R-410A at rated conditions, with R-32 exhibiting higher discharge temperatures by 11°C in cooling mode and 12°C in heating mode. The Seasonal Energy Efficiency Ratio (SEER) for R-32 was 3% higher than R-410A, while the SCOP remained the same. Interestingly, the SCOP increased by about 2% when the heating design value (PdesignH) was reduced by 20%. Ceiling-mounted air conditioners adopting R-32 underwent modifications to enhance the heat exchanger size and operational logic, aligning with the requirements of the Energy-related Products Directive (ErP). These modifications included a 28.5% reduction in the scroll compressor's displacement volume, a 23.1% decrease in oil quantity, and an 11.8% lower refrigerant charge than R-410A. Despite the 5% lower cooling capacity, the EER for R-32 was 2% higher at rated conditions. However, the heating capacity was 1% higher, but the COP was 6% lower than R-410A. The higher compressor frequency required for R-32 systems at rated conditions was due to the smaller displacement volume and lower volumetric efficiency, resulting in higher discharge temperatures by 12°C in cooling and 8°C in heating modes. Overall, the R-32 systems demonstrated a 25% higher SEER and a 27% higher SCOP compared to R-410A, reflecting a substantial improvement in seasonal efficiency. The transition to R-32, driven by stringent refrigerant regulations, has shown to be both environmentally beneficial and economically viable. With a GWP of just 32% R-410A and 20% lower refrigerant charge requirements, CO_2 emissions from R-32 are approximately 75% lower. These advantages, coupled with better performance metrics, make R-32 a compelling choice for future air conditioning systems, ensuring high efficiency and compliance with evolving environmental standards.

5. Review of Design Optimization and Advancement Impacts on LCCP Reduction

We reviewed the impact of design optimization on the LCCP of HVAC systems. The focus is on evaluating various refrigerants and their performance across different regions. Design optimization is pivotal in reducing the LCCP of HVAC systems in the U.S. Comprehensive assessments consider factors such as weather data, power factors, manufacturing embodied carbon emissions, and material usage to identify key contributors to carbon emissions. Regional comparisons reveal that annual energy consumption and refrigerant leakage are primary contributors to LCCP, with system efficiency being more crucial in high-GEF countries and leakage more significant in low-GEF countries. The Urban Heat Island (UHI) effect introduces discrepancies in LCCP calculations, highlighting the need for accurate local weather data. Low-GWP refrigerants like R-290 demonstrate substantial promise in reducing LCCP, particularly in low-GEF countries. Future work aims to expand evaluations to include new refrigerants such as R-466A, increase regional comparisons for a comprehensive global perspective, and explore the relationship between LCCP and cost to optimize performance economically.

Sweden's commitment to environmental sustainability is highlighted by research focused on the environmental benefits of reducing refrigerant charges in HVAC systems. By concentrating on low-GWP refrigerants and optimizing system designs, significant reductions in both direct and indirect CO_2 emissions have been achieved. Notable projects such as Eco Pack and ProPack demonstrate the feasibility of low-charge systems in delivering high efficiency. The integration of natural refrigerants and optimized component design results in substantial reductions in LCCP, underscoring Sweden's leadership in developing sustainable HVAC technologies that contribute to a greener future. Sweden's research also explores the potential of using automotive industry components, such as flat aluminum multi-port tubes and compact compressors, to reduce refrigerant charges further and enhance system efficiency. These innovative approaches highlight the potential for cross-industry collaboration to drive advancements in HVAC technology, ultimately contributing to significant reductions in greenhouse gas emissions.

In ***Germany***, holistic concepts for coupling building simulations with the needed load dynamics of a heat pump and the choice for a long-term usable refrigerant were developed to create tools for a more fundamental approach, considering the overall lifecycle of heat pumps [4]. Based on the results of an LCA and other selection criteria, such as the F-gas Regulation, a recommendation for action is made, and the use of R-290 in residential heat pumps is recommended. Another unpublished LCCP analysis from which only results were presented during the Annex 54 expert meeting in September 2021 [5] came to similar conclusions. With the environmental impacts of a heat pump determined, an ecological comparison is made between a heat pump and a gas-condensing boiler. As mentioned before, the efficiency of the heat pump and the origin of the purchased electricity significantly influence the environmental impact of a heat pump and, thus, the ecological comparison. For example, with a SCOP = 3.1 and a predicted increase in the share of renewable energies in the German electricity mix, a heat pump decreases greenhouse gas emissions over the entire life cycle by 54% compared to a gas condensing boiler. This is mainly limited due to the high material needed to produce a heat pump. Both studies compared different refrigerants and forecasted drastic changes in the share of fossil-fuel-generated electricity in the next two decades. Here, the decreasing share of indirect emissions due to greener electricity production leads to significant differences in the overall CO_{2e} emissions during the lifecycle of a heat pump. Indirect emissions shrink to about only 20% compared to the situation in Germany in 2020. This should be incorporated into the decision-making processes for future-proof low-GWP refrigerants.

Japan provided an in-depth analysis of the LCCP and risk evaluations for heat pump systems using low GWP refrigerants. This study aims to identify suitable refrigerants, assess their environmental impact, and evaluate safety measures to mitigate risks. The LCCP evaluation follows guidelines from the International Institute of Refrigeration and examines refrigerants like R-410A, R-32, R-454C, R-290, and R-22. Direct emissions are based on refrigerant charge, leakage rates, and end-of-life emissions, while indirect emissions come from energy consumption over the equipment's life. Using the JRAIA standard model, the analysis simulates cooling and heating conditions to determine annual energy consumption and refrigerant charge. Risk assessments cover stages from logistics to disposal, analyzing ignition probabilities and flammable spaces. Findings show minimal risks during transportation and storage with proper safety measures. During installation and service, risks are reduced through training and leak detection devices. In the usage phase, mechanical ventilation and refrigerant leak detectors are recommended. Proper recovery and training are crucial for safe dismantling and disposal. R-32 and R-290 are highlighted as promising refrigerants due to their lower GWP and performance, though they require different risk mitigation strategies. R-32 offers a balance between performance and environmental impact but needs careful handling due to mild flammability. R-290 has excellent thermodynamic properties and very low GWP, but it poses significant flammability risks that require rigorous safety measures. The report stresses the importance of comprehensive safety protocols, including mechanical ventilation, refrigerant leak detectors, and personnel training across all life cycle stages. Regulatory compliance with standards like ISO 5149 and JIS B 8623 is vital. Innovative technologies and best practices are crucial for enhancing the safety and efficiency of systems using low-GWP refrigerants. The transition to low-GWP refrigerants is essential for reducing the environmental impact of heat pump systems. The report concludes that balancing environmental benefits with safety concerns is key to this transition. LCCP evaluations and risk assessments provide a robust framework for implementing these refrigerants. This analysis guides policymakers, industry stakeholders, and researchers in advancing the use of low-GWP refrigerants in Japan and potentially other regions. With the right safety measures and international compliance, low-GWP refrigerants can be adopted efficiently and safely, promoting sustainability in the HVAC industry and supporting efforts to combat climate change and promote sustainable development.

The ***Austria*** report focuses on the LCCP of heat pump systems, emphasizing the impact of transitioning from high-GWP refrigerants to low-GWP alternatives, specifically R-290. National and international regulations aim to reduce the greenhouse gas emissions caused by the release of refrigerants into the atmosphere by defining restrictions for refrigerants with high GWP values in certain applications and limiting the total CO_2 equivalent of refrigerants on the market through a phase-down concept. However, most used refrigerants currently have GWPs of a magnitude of 1000 or even more. While natural refrigerants like R-290 and R-600a can easily be used in other sectors like refrigerators or freezers, the situation is different for heat pumps due to higher capacities and refrigerant charges. In IEA HPT Annex 54, the potential replacement of conventional (high GWP) refrigerants by so-called Low GWP refrigerants (e.g., R-290) and its implications are investigated. The LCCP evaluation is based on the investigations regarding the technical implications of changing a heat pump system from an R-410A baseline system to a charge-optimized R-290 system using Modelica simulations in a case study of Task 2. This third Task focuses on the impact of these system adaptations on the LCCP of a heat pump system. Unified calculations were performed to determine the LCCP of the R-410A baseline system and the charge-optimized R-290 system to achieve comparability. The LCCP was calculated using the software Pack Calculation Pro. As this calculation tool excludes indirect emissions from equipment manufacturing, equipment recycling, and refrigerant manufacturing, this missing emission share was calculated with the Excel-based tool IIR-LCCP-Calculation-Tool (IIR, 2016). The investigations show that the charge-optimized R-290 system does not only perform better regarding direct CO_{2e} emissions (refrigerant leakages) due to its very low GWP but also due to better energy efficiency and better thermodynamic properties. Based on the leakage rates proposed by IIR (2016), the direct CO_{2e} emissions due to refrigerant leakage and end-of-life refrigerant losses of the R-410A baseline system would account for approx. 38.3 tons CO_{2e}, those of the charge optimized R-290 system to only 8 kg. The (electrical) energy consumption of the R-410A baseline system during its lifetime leads to indirect CO_{2e} emissions of approx. 20.3 tons CO_{2e}. Due to better thermodynamic properties, the respective value of the charge-optimized R-290 system is significantly lower (16.6 tons CO_{2e}). The direct CO_{2e} emissions from refrigerant leakage and the indirect CO_{2e} emissions due to the (electrical) energy consumption sum up to a Total Equivalent Warming Impact (TEWI) of approx. 58.5 tons CO_{2e} (R-410A baseline system) resp. 16.6 tons CO_{2e} (charge optimized R-290 system). Adding indirect CO_{2e} emissions from manufacturing and recycling the LCCP of the R-410A baseline system and the charge-optimized R-290 system is calculated to approx. 59.6 tons resp. 17.4 tons CO_{2e}. To better understand the significance of these values, the TEWI values were compared with the lifetime CO_{2e} emissions of a comparable natural gas-fired heating system: the latter would account for CO_{2e} emissions of approx. 128 tons CO_{2e}. In relation to this value, the TEWI values of the R-410A baseline system and the charge-optimized R-290 system are 46% resp. 13% of this value. The deviation in performance between the R-410A baseline system and the charge-optimized R-290 system supports the call for replacing conventional refrigerants with Low GWP refrigerants. Reducing the refrigerant charge and improving refrigerant leakage rates are further valid approaches for improving the LCCP of heat pump systems.

Furthermore, it should be mentioned that for Austria's domestic heat pump market, the actual refrigerant leakage rate and end-of-life refrigerant leakage might be lower than assumed in this investigation. As in Austria, the exact situation regarding refrigerant leakages is unknown; the assumptions in this investigation were made as recommended by the IIR. In the future, comprehensive investigations regarding the actual refrigerant leakage situation in Austria's domestic heat pump market are highly recommended. The importance of using heat pumps with low-GWP refrigerants has increased considerably in Austria in recent years and has become much more important due to climate targets.

The refrigerant charge reduction of refrigerants with a high GWP required by the European F-Gas Regulation can play a key role in combating climate change from a global perspective. This applies, in particular, to the use of refrigerants in countries with less stringent rules for avoiding direct refrigerant emissions or where compliance with these rules cannot be adequately monitored. The simulation study regarding modifications required to operate a former R-410A heat pump with R-290 instead showed that major modifications need to be considered. In addition to safety precautions due to the flammability of R-290, a compressor with a larger displacement is required due to the lower volumetric cooling capacity of R-290. Other changes concern larger pipe diameters, and the dimensioning of the expansion valve must be reviewed. For safety reasons, in particular, technologies to reduce the amount of refrigerant have great potential and will continue to be of great importance in the future. Many components, such as the compressor, condenser, receiver, expansion valve, and evaporator, must be considered. The LCCP analyses carried out in the project showed that heat pumps with R-290 not only perform better in terms of direct CO_{2e} emissions (refrigerant leakage) than those with R-410A (8 kg compared to 38 tons of CO_{2e}) but also have higher energy efficiency due to better thermodynamic properties (around 18% lower electricity consumption), which resulted in further savings of 3.7 tons of CO_{2e}. According to the calculations, replacing a natural gas heating system with a heat pump system using R-410A would save just over 50% of CO_{2e} emissions, while replacing it with an R-290 system would save almost 90%. However, it should be noted that the leakage rates of the heart pumps in Austria are likely to be lower than the standard values used in this study, according to IIR (2016). For this reason, more in-depth investigations into the actual leakage situation in Austria are recommended.

6. Outlook for 2030

We made a forward-looking perspective on the future of low-GWP refrigerants in the HVAC&R industry, outlining research directions and technological advancements. Looking towards 2030, the future of low-GWP refrigerants in the HVAC&R industry in the **US** is promising, with ongoing research, regulatory advancements, and technological innovations set to drive further progress. Research directions will focus on comprehensive evaluations of refrigerants like R-466A and other potential A1 refrigerants, alongside in-depth safety studies on A2L and A3 refrigerants to address safety challenges. Beyond low-GWP refrigerants, there is an exploration of zero or near-zero GWP refrigerants and innovative system designs to achieve minimal environmental impact. Regulatory trends in the U.S., Europe, and China are increasingly supportive, with continuous updates to safety standards facilitating the adoption of low-GWP refrigerants. Technological advancements will see the development of new system configurations and refrigerant blends to enhance efficiency and reduce environmental impact alongside advanced optimization techniques crucial for meeting sustainability goals.

In ***Germany***, the transition to low-GWP and – in almost all cases – flammable refrigerants is ongoing, and the political framework meant an important incentive for new heat pump developments. The application of R-290 as refrigerant is important for an optimal approach to energy savings. It will increase its importance in the next years until 2030, since hydronic-based heat pump installations started to dominate the European heat pump market in 2021. Charge-reduced components will also pave the way for more heat pump types to be charged with this refrigerant. However, certain alternative refrigerants might remain on the market. This will mainly depend on safety regulations for their target markets. However, climate warming will reduce the need for heating in general, and global studies already forecast that cooling and hot water production will play a more significant role in the future. This could lead to a quick shift backward again and favor air-based heat pumps and domestic hot water heat pumps, which still have a small market share for hot water production. For hot water heat pumps, R-290 is likely to dominate in the future due to the small charge amount needed. The refrigerant R-32 is mainly used nowadays. Here, it is very probable that blends with halogenated refrigerants and flammable refrigerants will be explored to balance performance and safety, potentially leading to new formulations that optimize efficiency and minimize environmental impact. First systems for indoor usage of R-290 have already entered the market in Germany, and the forecast for 2030 suggests that this trend will extend to larger systems for multi-family houses. However, other low-GWP refrigerants will also play a role. Due to safety issues—often exacerbated by a lack of knowledge about the spectrum of available safety measures—stakeholders must prioritize education and training. This is still valid for all developing heat pump markets where the transition has not yet started. Here, stakeholders should recognize the importance of decarbonization, emphasizing that advancing the use of low-GWP refrigerants in heat pumps is essential for achieving climate goals.

Regarding future developments, the ***Australian*** forecast market potential for heat pumps is around 60,000 units per year in 2030 (BMVIT, 2016), but experts assume that even 80,000 to 100,000 units will be used annually in 2030. In 2021, this figure was 31,000 units per year. Regarding the potential of low-GWP refrigerants, stakeholder surveys performed in Austria in relation to IEA HPT Annex 60 revealed a wide range of possible developments. While one stakeholder segment sees propane (R-290) as the market leader for 2030, another assumes that the bans on conventional refrigerants in the F-Gas Regulation will be overturned. Yet another segment favors HFO-based refrigerants in their assessments.

7. Conclusions

In summary, the HVAC&R industry's transition to low-GWP refrigerants is essential to mitigating global warming and complying with international environmental agreements. Technological advancements in refrigerants, system components, and design innovations are crucial to improving efficiency and reducing environmental impact. A1 refrigerants like CO_2 and R-466A, A2L refrigerants like R-32 and R-454B, and A3 refrigerants like R-290 offer promising alternatives to traditional high-GWP refrigerants. However, each presents unique challenges that must be addressed through rigorous evaluation and optimization. The regulatory landscape is vital in facilitating this transition, with international agreements and stringent regulations promoting the adoption of low-GWP refrigerants. Ongoing research into thermophysical properties, heat transfer characteristics, and safety measures is critical to ensuring these refrigerants' safe and effective use in HVAC&R systems. The comprehensive analysis conducted within the Annex 54 activities guides the industry, highlighting the importance of balancing performance, environmental impact, and safety in pursuing sustainable HVAC&R solutions.

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