Technology Collaboration Programme
by iea

Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

Annex 54

Heat Pump Systems with Low-GWP Refrigerants

Country Report Germany

Author/s:
Thore Oltersdorf, Lena Schnabel,
Christian Vering

November 2024
Report no. HPT-AN54-6

Published by Heat Pump Centre
c/o RISE – Research Institutes of Sweden
Box 857, SE-501 15 Borås
Sweden
Phone +46 10 16 53 42

Website https://heatpumpingtechnologies.org

Legal Notice

Neither the Heat Pump Centre nor any person acting on its behalf:
(a) makes any warranty or representation, express or implied, with respect to the information contained in this report; or
(b) assumes liabilities with respect to the use of, or damages, resulting from, the use of this information.
Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement recommendation or favouring.
The views and opinions of authors expressed herein do not necessarily state or reflect those of the Heat Pump Centre, or any of its employees. The information herein is presented in the authors' own words.

Production Heat Pump Centre, Borås, Sweden

DOI: https://doi.org/10.23697/60sn-m236
Report No. HPT-AN54-6

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.

Disclaimer

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:
Heat Pump Centre
c/o RISE - Research Institutes of Sweden
Box 857, SE-501 15 BORÅS, Sweden
Phone: +46 10 516 53 42
Website: https://heatpumpingtechnologies.org

Executive Summary

This country report for Germany evaluates the state-of-the-art technologies in heat pump systems for several years, focusing on the findings from large-scale field tests and funded projects of different institutions dealing with R&D topics of applying low-GWP refrigerants. The key aspects covered in the report include:

Funded Projects and Technological Development

In several case studies, the report shows the diverse spectrum of heat pump research working in the field of applying low-GWP refrigerants. It reports on the diverse spectrum of institutions involved in this process for evaluation, development of refrigerants, refrigerant-oil mixtures, and components, as well as systems for heat pumps mainly operated as vapor compression systems. Here, not only efficiency but also safety topics are applied to cope with the increasing flammability of low-GWP refrigerants. Charge reduction measures for optimized and safer cycle design and for the safety analysis after a release in case of a leakage. Next to vapor compression heat pumps, the research investigated tumble dryers, thermal management systems for electric vehicles (buses) as well as hybrid and absorption heat pumps.

Market analysis

Through a thorough analysis of product data as well as funding applications, the supply side and the demand side were studied. Based on this, the transition process to low-GWP refrigerants for residential heat pumps was investigated. It was shown by the analysis of the supply side (product databases) that already available products of R290 heat pumps usually have the highest achievable performance. The first significant run for R290 residential heat pumps was in 2012, but no data on their market share was available. A continuous dataset has been available for the time since 2016. The introduction of new R290 heat pumps in 2018 led to a recognizable share starting from 2019. For heat pumps in residential houses, this resulted in a 20% share for all heat pump types in 2023. The first increase in its share for R32 systems started about one year later, in 2020. Until now, R32 as refrigerant gained even a larger share but reflects systems that are mainly imported to the German heat pump market. The share of R410A systems is still at about 40% in 2023. However, the significant drop in R410A share, as well as the added production capacity due to the forecasts for higher volumes of sold units since 2022, makes a complete transition probable to low-GWP refrigerants in accordance with the F-gas regulation.

Insights in the heat pump performance based on field tests

Continuous monitoring of heat pump systems since 2006 has been performed, including the latest projects, which concluded in 2019. These studies have primarily focused on assessing the efficiency of heat pumps, their capability to operate in a "smart mode" which interacts efficiently with renewable electrical energy sources, and the CO_2 avoidance potentials. The latter depends highly on the CO_2 equivalent emissions by the electrical energy production for which the share changed during the duration of Annex 54 from 29% in 2016 to 53% in 2023[1].

[1] www.energy-charts.info

5.1 Review of state-of-the-art technologies in 2020

Thore Oltersdorf[1]*, Lena Schnabel[1], Timo Methler[1], Clemens Dankwerth[1], Simon Braungardt[1], Nikhil Mittapalli[1], Christian Vering[2], Dirk Müller[2], Katharina Stöckel[3], Ramona Nosbers[3], Christiane Thomas[3] Ullrich Hesse[3], Wilhelm Tegethoff[3], Niklas Brandt[3]

[1]Fraunhofer Institute for Solar Energy Systems (ISE), Department Heating and Cooling Technologies

Freiburg, Baden-Wurttemberg, Germany

[2]RWTH Aachen, E.ON Energy Research Center, Institute for Energy Efficient Buildings and Indoor Climate

Aachen, North Rhine-Westphalia, Germany

[3]Technical University Dresden, Bitzer-Chair of Refrigeration, Cryogenics and Compressor Technology,

Dresden, Saxony, Germany

[4]Technical University Braunschweig, Institute for Thermodynamics,

Braunschweig, Lower Saxony, Germany

*** Corresponding Author, Thore Oltersdorf (thore.oltersdorf@ise.fraunhofer.de)**

Department Heating and Cooling Technologies Group Component and System Heidenhofstrasse 2, 79110 Freiburg, Germany

5.1.1 Introduction

To evaluate the state-of-the-art technologies, it was decided to report on three issues:

- Most recent findings of the field test for heat pumps based on the findings of the funded project "WP Smart im Bestand", FKZ 03ET1272A.
- A review of the funded projects (until now) based on the enArgus database (www.enargus.de).
- BAFA results on the use of refrigerants back in the year 2016.

The second issue is not necessarily a well-reflecting figure on state-of-the-art, but it is a useful starting point to understand what kind of changes in refrigerants could occur – at least partially – in the German market within the next years.

5.1.2 Field tests for heat pumps

5.1.2.1 Introduction

In Germany, large monitoring heat pump field tests have been executed since 2006. In an uninterrupted series of monitoring projects since this time, projects with different manufacturers were realized with about 200 residential houses. In most recent projects that ended in 2019, a project dedicated to quantifying (1) the most recent efficiency and (2) the potential to operate heat pumps in a "smart-mode" to interact as beneficially as possible with renewable electrical energy production.

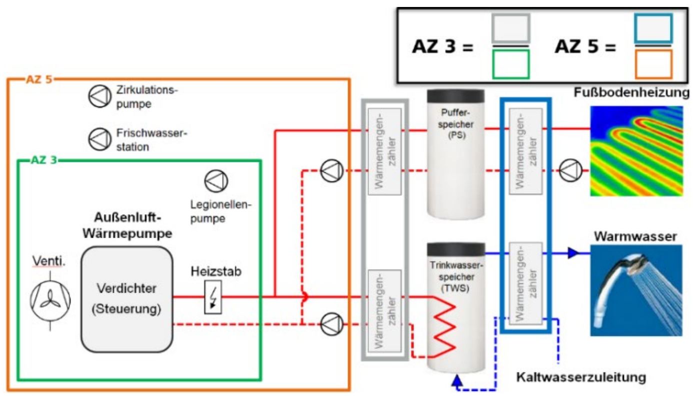


Figure 5-1: System limits for the calculation of seasonal performance

5.1.2.2 Recent findings

To be able to reconstruct the efficiency values, the balance limits 3 and 5 are presented on the basis the, exemplarily for an outside air heat pump. With the balancing limit 3 (AZ[1] 3) the thermal energy made available by the heat pump for space heating and TW-warming is measured directly after the heat pump, thus before any storage tanks (grey). As input, the necessary electrical energy of the compressor, control, heat source drive (fan or brine pump), and electrical heating element is considered. The legionella pump shown serves to mix the TW storage tank and is only very rarely part of the installation (green). At the AZ 5, the thermal energy is measured after any storage tanks (blue). The electrical energy consumers correspond to those of AZ 3 plus the storage charging pumps, the circulation pump, and the pump for the fresh-water station.

Figure 5-2 (22 air-to-water heat pumps) and Figure 5-3 (9 ground-source heat pumps) show the annual working figures (AWP) of AZ 3 (light grey) and AZ 5 (dark blue). The selection of systems is limited to those heat pumps to which both balance sheet limits apply. To the left of each SPF, the energy produced by the heat pump is shown proportionally according to room heating (red) and domestic hot water heating (blue). Furthermore, the graphs show the flow and return flow temperatures measured before the storage tanks as well as average temperatures in room heating (orange rhombus) and drinking water heating mode (blue rhombus). The maximum drinking water tap temperatures are shown in the form of blue triangles. The systems are sorted in ascending order according to the percentage difference between SPF 3 and SPF 5.

[1] AZ stands for German "Arbeitszahl", the seasonal performance figure.

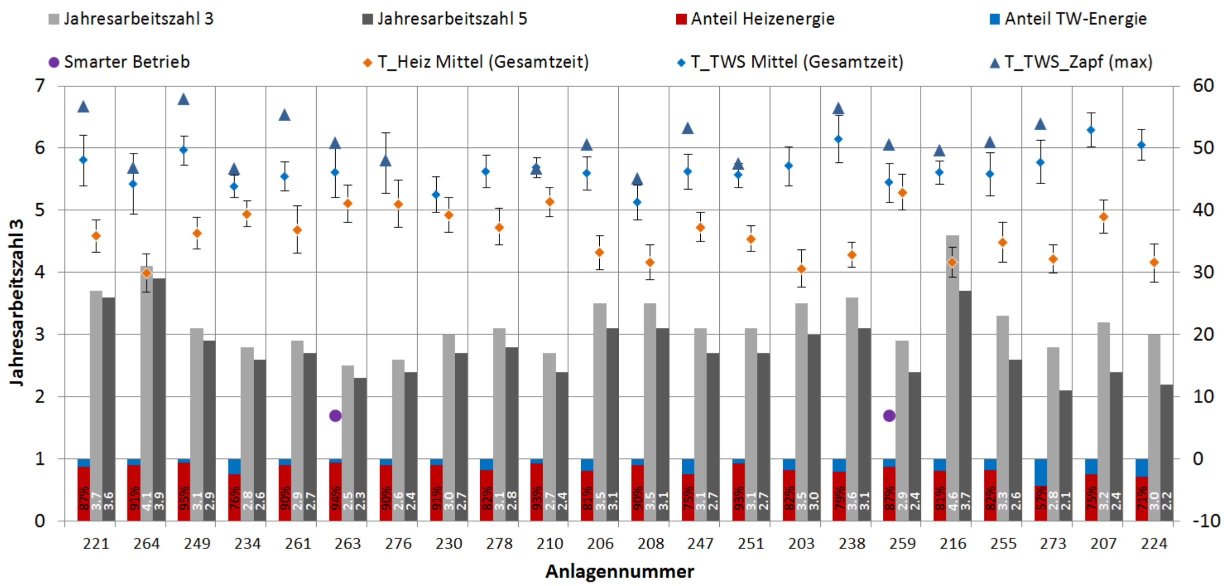


Figure 5-2: Annual SPF of the balancing limits AZ 3 and AZ 5 as well as temperature and energy values of 22 outdoor air-to-water heat pumps sorted by the percentage difference of both annual performance factors

For outdoor air heat pumps, the range of SPF values for the balancing limit AZ 3 is between 2.5 and 4.6, with an average value of 3.2. The SPF value range for systems with the balancing limit AZ 5 is between 2.1 and 3.9, with an average value of 2.8. Remarkable are the big differences between the JAZ of both balancing limits, which are between 3% and 27% (average value: 13%). Although the additional electrical energy consumers (see above) also play a role in AZ 5, the main influence is caused by storage losses. The main drivers are thus the average temperatures in the space heating buffer storage tank (BS, in German PS) and in the domestic hot water (DHW, in German TWS) storage tank as well as the energy shares between the two operating modes. Since the storage tank temperatures were not measured, the storage tank charging temperatures are used here in a simplified way. Except for a single ground-source heat pump investigated within the project (not considered here), the average heating circuit temperatures are always below the average DHW charging temperatures. Thus, both an increase in the difference between DHW and BS charging temperatures and an increase in the energetic share for DHW heating should contribute to an increase in the difference between SPF 3 and SPF 5. This trend can be traced using the quantities shown in Figure 5-2. For ground-source heat pumps, the SPF value range for the balancing limit AZ 3 (for AZ 5 in brackets) is between 3.3 (2.9) and 4.6 (3.8), with an average value of 3.9 (3.3). The deviation between the two SPF values is between 9% and 24%, with a mean difference being 15%. The correlations between these differences and the temperature differences (for space heating or domestic hot water heating) as well as the energy shares for domestic hot water heating visible for the outdoor air-to-water heat pumps, cannot be observed for the ground-source heat pumps. Only the three highest energy shares for domestic hot water heating can be assigned to the heat pumps with the three highest JAZ differences.

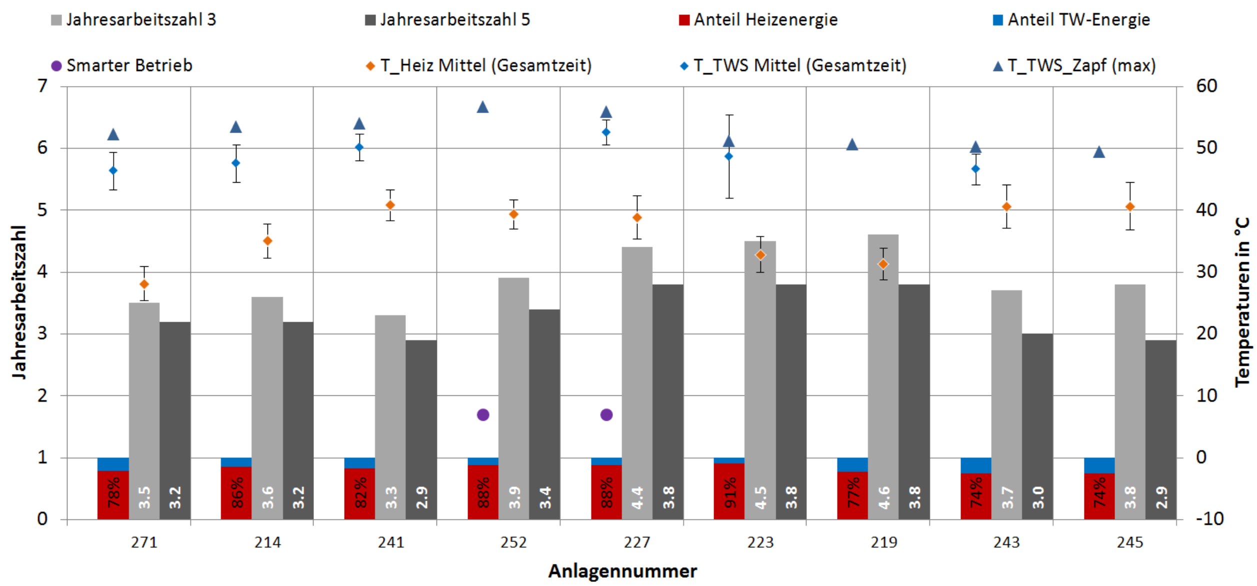


Figure 5-3: Annual SPF of the balancing limits AZ 3 and AZ 5 as well as temperature and energy values of 9 ground source heat pumps sorted according to the percentage difference of both annual performance factors

In the Figure 5-4 different types of heat pump system configurations are clustered to present the share of CO_2 represented by the employment of this heat pump instead of a gas device. A differentiation according to heat source types is not (yet) made here. The first group (left) contains all heat pumps that can be evaluated for the balance limit 3. Except for one system (-5%), CO_2 emissions of 25% to 60% would be avoided. The average value is 42.6%. The second group also refers to the balance limit 3, but only considers the room heating mode. It is remarkable in this group that exactly one heat pump has a better YES in-room heating mode than in domestic hot water heating mode. This shifts the already negative CO_2 avoidance of this one system to -9%, while the CO_2 avoidance of all other systems increases and averages 47.1%. Including (the 3rd group) the plants that were still operated "smart" during the evaluation period and thus usually had higher heating circuit temperatures, the values of CO_2 avoidance shifted slightly downwards. Those plants are considered in the 4th group only, which can be evaluated for a balance limit of 5. This means the system is comprehensively evaluated, including storage losses and all electrical energy consumers (apart from heating circuit pumps). Assuming this balance limit, the values for CO_2 avoidance are between 9% and 52%, with an average value of 33.3%.

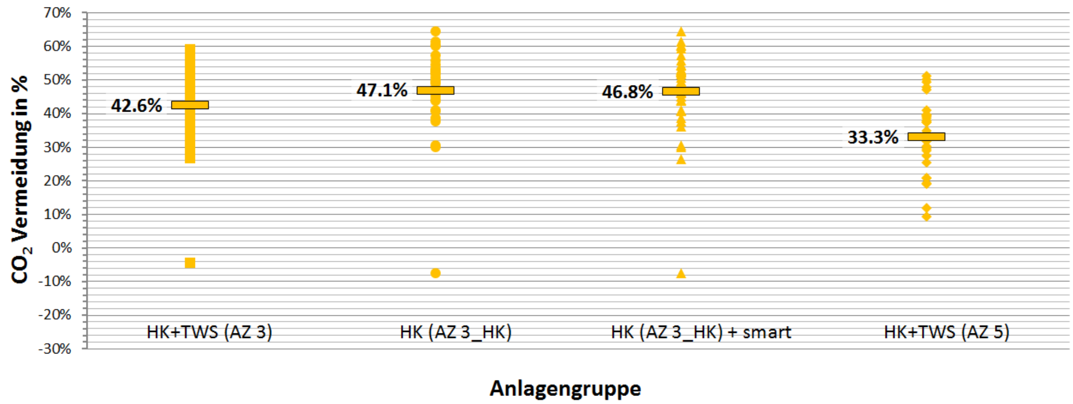


Figure 5-4: CO_2 avoidance potential of the examined heat pumps, differentiated according to balancing limits AZ 3 or AZ 5, the operating mode (space heating and domestic hot water heating), and additionally a "smart operated"-mode when replacing a gas boiler

5.1.2.3 Refrigerants in heat pumps that have been tested in the field test

While more and more units with alternative refrigerants, such as R290 (propane), came onto the market towards the end of the project term, the traditional refrigerants dominate in the systems investigated here. As Figure 5-5 shows, more than half of the heat pumps are operated with R410A (GWP: 2,088) and about a quarter with R404A (GWP: 3,922). Furthermore, the refrigerants R407C (GWP: 1,744) and R134A (GWP: 1,430) are also present. Only one plant uses the alternative refrigerant R290 (propane, GWP: 3). For one system the used refrigerant type was unknown (in German: unbekannt).

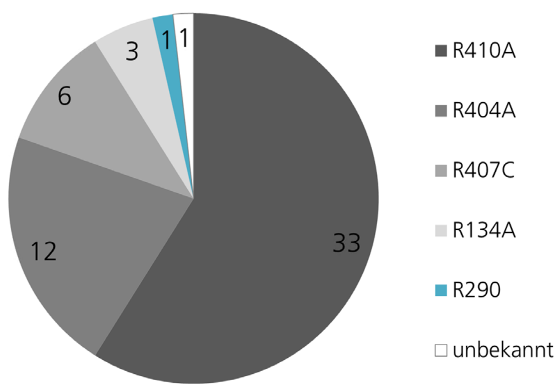


Figure 5-5: Share of used refrigerants

5.1.3 Review of funded projects

By analysing the BMWi project database EnArgus[1] it is possible to gather information on the energy-related on all projects (running or terminated) on any field of interested. The database was filtered for the keywords "heat pump" (in German: Wärmepumpe) and "refrigerant" (in German: Kältemittel). Only project that were started with January 2015 were investigated. Since then, the number of projects related to the keyword "heat pump" were 241 running projects. The number of

[1] www.enargus.de

projects was too large to figure out which project actively developed new refrigerant circuits since not all project reports were available yet or not at all available.

However, the resulting group for “heat pump” had a large intersection with another result group when searching for “refrigerant.” The number of projects related to the term “refrigerant” were 19 projects. From Figure 5-6 it becomes clear that the focus on the new development of cycles often uses so-called natural refrigerants. It is avoided to state here that natural refrigerants dominate new developments since there were more than 240 heat pump projects. However, the major share of projects probably serves this goal. As expected, many projects focus on vapor compression systems as the investigated thermodynamic cycle, see Figure 5-7.

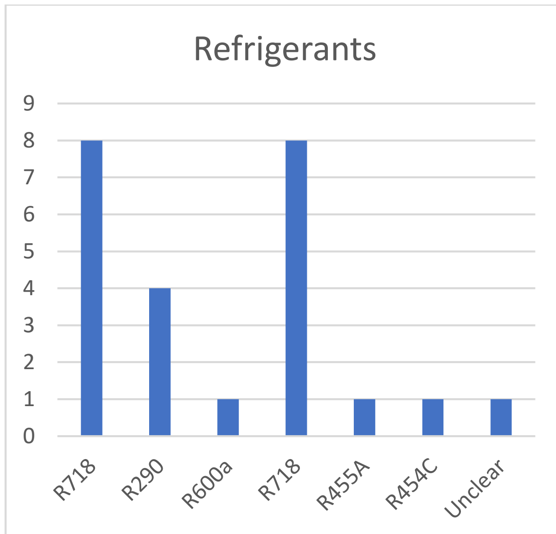


Figure 5-6: Range of refrigerants in energy-related projects in Germany related to the new development of thermodynamic cycles

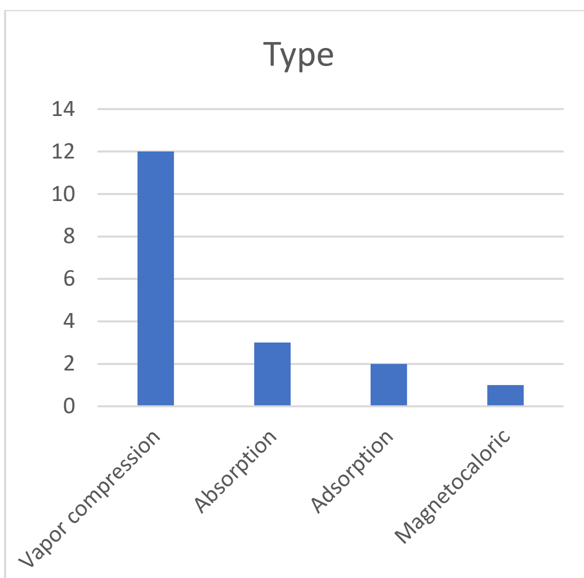


Figure 5-7: Range of different thermodynamic cycles being investigated in energy-related projects in Germany

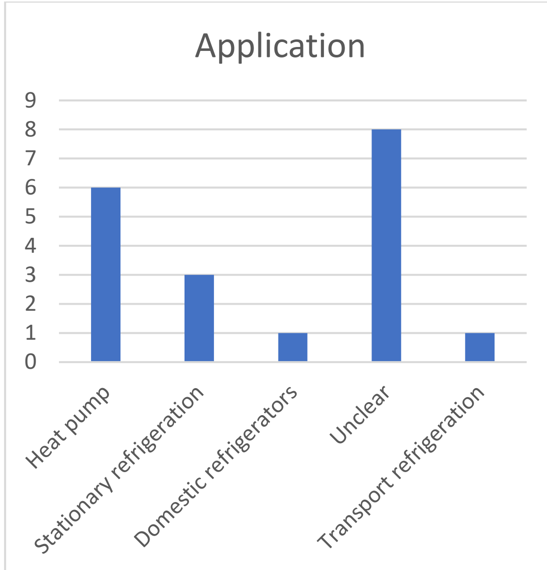


Figure 5-8: Range of the type of applications being investigated in energy-related projects in Germany

From the application type that could be identified also, heat pumps play a major role in innovative systems that are investigated in Germany (see Figure 5-8).

5.1.4 Analysis of BAFA data

As a third part of this report on the state-of-the-art technologies, the BAFA data on heat pumps for what a financial incentive is given to support renewable thermal energy production for heat supply in residential houses. It was tried to gather information on the most important manufacturers, their overall number of air-to-water heat pump models using a frequency inverter that is supported, and the share of refrigerants being used.

The following list of manufacturers and their portfolio for June 2016 as well as for June 2020 was investigated: ait-deutschland, Bosch Thermotechnik, Daikin, Fujitsu, Glen Dimplex, Heliotherm, Mitsubishi Electrics, Ochsner, Panasonic, Remko, Samsung, Stiebel Eltron, Thermia, Vaillant, Viessmann, Waterkotte, Weishaupt, Wolf.

To identify which systems were only available in 2016, all heat pumps listed in the 2020 table were negated. Overall, 2731 models could be identified as being supported in 2016 compared 4502 models being supported in 2020. In 2016, from about 402 models, the refrigerant could be identified based on the list of manufacturers and the information that could be gathered. In 2020, the same number could be gathered for 4502 models. The search was not supported by any manufacturer and was based on research on a manufacturer’s website.

Below in Figure 5-9 the share of refrigerants is Figure 5-10 for both years are displayed.

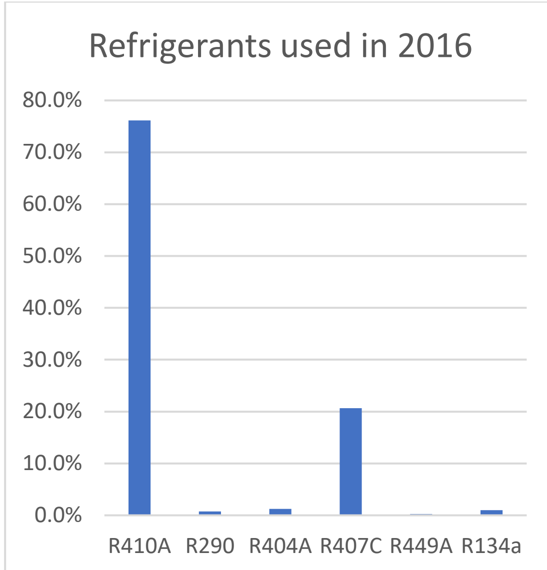


Figure 5-9: Refrigerants being used in heat pumps listed in the BAFA tables in 06/2016.

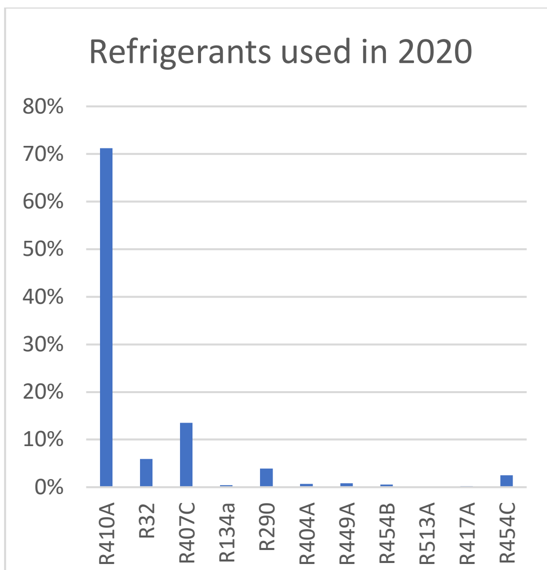


Figure 5-10: Refrigerants being used in heat pumps listed in the BAFA tables in 06/2020.

5.1.5 References

[1] A New Mixture Refrigerant for Space Heating Air Source Heat Pump: Theoretical Modelling and Performance Analysis - Xiangrui Kong, Yufeng Zhang; Jinzhe Nie, Tianjin University - Appl. Sci. 2018, 8, 622 ; doi:10.3390/app8040622.

[2] Next generation of refrigerants for residential heat pump systems - Martina Longhini – Thesis report Stockholm 2015.

[3] Effectively Managing the Transition to Lower GWP Refrigerants, Karim Amrane, Air-Conditioning, Heating, and Refrigeration Institute – 12th IEA Heat Pump Conference Rotterdam 2017.

[4] Multi-criteria decision making analysis in refrigerant selection for residential heat pump systems Pavel Makhnatch, Hatef Madani, Rahmatollah Khodabandeh, KTH Royal Institute of Technology, Department of Energy Technology - Sweden – 12th IEA Heat Pump Conference Rotterdam 2017

[5] AHRI, http://www.ahrinet.org/Resources/Research/AHRI-Low-GWP-Alternative-Refrigerants-Evaluation-Program/Reports-by-Category#ACHP

[6] OSTI, https://www.osti.gov/search/semantic:heat%20pump%20water%20heating/page:2

5.2 Case studies and design guidelines for optimized components and systems in 2020

5.2.1 Summary

This task report tries to focus on design guidelines related to Annex 54 activities and case studies that are either part of it or so close in its topics (related to low-GWP R&D activities – as with the work of TU Braunschweig, TU Dresden, and RWTH Aachen) that it was included. Safety research activities are not well defined as activities within the legal text, and thus, it was interpreted as being part of the design guidelines that could be developed as part of Task 2.

The German task report does not claim in any sense to clarify comprehensively all activities in Germany. To some extent, these findings include component-level activities (TU Dresden), which are closer to Task 1 topics and not only case studies addressing Task 2 topics. However, the case studies are focused on different types of domestic heat pumps (Fraunhofer ISE) as well as laundry dryers (TU Braunschweig, TU Dresden) and – in one case – a refrigerator (TU Dresden). The topic of multi-objective decision-making tools used by RWTH is a bit exceptional, and there is no experimental approach. Nevertheless, it could be categorized as a design guideline to select the bank of feasible refrigerants, as discussed in Task 1.

5.2.2 System developments and refrigerants put into focus

5.2.2.1 Background and Introduction

This section contributes to a better understanding of the market situation for heat pumps in Germany. It continues the survey of Germany's Task 1 report. In a development context, two groups of refrigerants are the focus of manufacturers:

- A2L (mainly R454C, R452B and R32) as well as
- A3 (almost only R290, on a small scale R744, too).

A small share of R290 systems is already – even on a long-term scale – market-available; these are:

- small exhaust air heat pumps for passive houses or similar buildings with small heat loads, or solely small types dedicated for domestic hot water production,
- ground source heat pumps, as well as
- outdoor air-to-water heat pumps.

5.2.2.2 Outlook

Research is ongoing for both refrigerant groups and all three types of domestic heat pump systems. Of course, the activities are more diversified for A2L than A3 refrigerants. The main objective is to improve and increase the availability of safe, acoustically optimized, energy-efficient, and robust outdoor monobloc air-to-water heat pumps. One decisive step is the ongoing development process of appliances that allow low-charge indoor mounted heat pumps, which have been applied in several projects.

For R&D development projects, the situation is not that much different from activities for A3 appliances. An ample range of heat pumps operated with F-Gases is also available or under development. For this reason, no itemized list is placed here on the types of F-Gases used. The trend in R&D activities does not only comprise the introduction of refrigerants for single-family houses. In a few years, it will also include R&D activities for new large-capacity heat pump models for multi-family dwellings. In Germany, the share of multi-family houses and rented flats is high, and the decommissioning of old equipment and substitution (partially with heat pumps) is expected to increase soon.

5.2.3 Design guidelines related to safety for heat pumps operated with A3 refrigerants

5.2.3.1 Background and introduction

The national project comprises, as part of the Annex 54 work CFD simulations to uncover safety issues for 10 different installation scenarios adjacent to residential houses. This topic is not precisely described within Task 2 of the legal text. Still, several national partners and participants within Annex 54 have referred to the safety issues that are related to A3 refrigerants.

This work is conducted by Fraunhofer ISE and is ordered by the Federal Ministry of Economic Affairs and Energy. The work is still ongoing and was mainly realized by a Master's Thesis [1] and a student specialized in CFD simulation. Results are expected to be finished for all cases by mid-2021. The results will be incorporated into the final report of Annex 54.

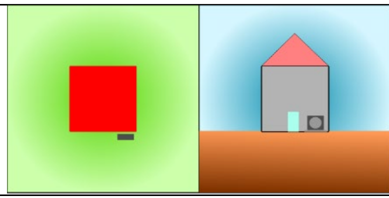
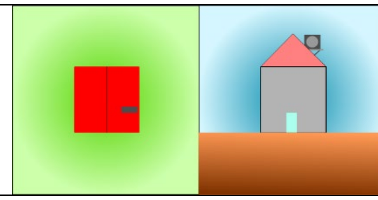
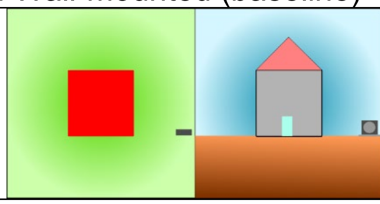
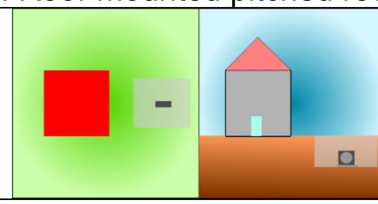
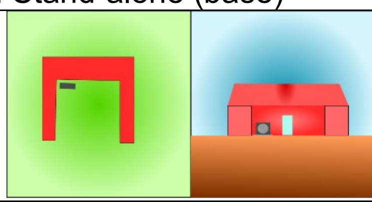
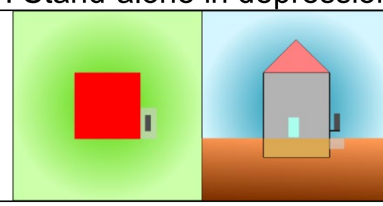
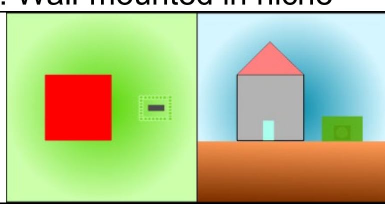
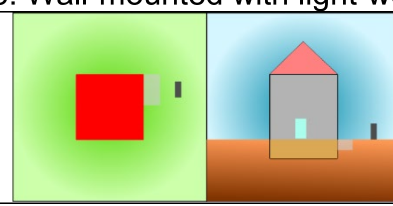
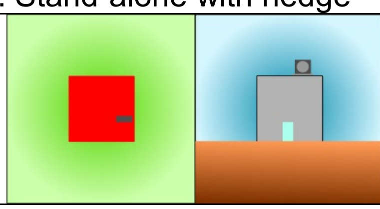
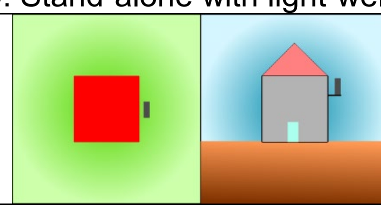
The standard IEC 60335-2-40 provides safety requirements for flammable refrigerants, which helps to reduce the risk of using them. As the heat pump unit could be in a partially closed environment (garage, sink in the ground, etc.), it can easily leak into the surroundings with unacceptable high residual times that could lead to gas concentrations larger than 20% LFL and smaller clouds with such isopleths. It is required to know the orientation and dimension of such a cloud so that preventive measurements like sensors can be established or installation instructions adapted. The aim of these simulation campaigns is to give guidance for experimentally realized tests according to IEC EN 60335-2-40. Clouds and isopleths at different concentration profiles of interest are simulated or calculated in a post-processing step.

The direct way to know the position of the gas cloud quantitatively is through experiments. However, direct physical testing requires a heavy initial investment and time to set up. Despite that, the measured data resolution is limited, and only certain testing conditions can be considered. So, the known alternative to experimental testing is computational fluid dynamics, which provides numerical data with high resolution. This high-resolution data provides an opportunity to understand and interpret the results better and optimally, which could simplify any experimental procedure.

The work in [2] and [3] describes the importance of a numerical approach to calculate the spread of flammable refrigerants in closed spaces. The challenge with numerical simulation is finding a way to evaluate the simulation results. The typical way to evaluate simulation results is to compare them with experimental results [4] and [5]. If experimental results are not provided, a mesh dependency study is performed. Also, as the simulation of the gas leak is time-dependent, studying the properties of the cloud at a specific point in time is not enough. It does not extol the nature of its complete transient behavior. So, the leakage has to be studied with respect to time throughout the simulation.

Many commercial software programs are available in the community to perform gas dispersion simulations. Most companies use commercial packages like Flacs (especially designed for safety analysis in chemical plants or offshore oil platforms, etc.), Fluent, and CFX. There are also a few open-source packages like Open-FOAM (OF) and Fire Dynamics Simulator. Commercial packages are user-friendly but have limitations in developing your own solvers and editing existing code to opt for your simulations.

Table 5-1: Survey on the ten different scenarios that were defined.

	
Case 1: Wall-mounted (baseline)	Case 6: Roof-mounted pitched roof
	
Case 2: Stand-alone (base)	Case 7: Stand-alone in depression
	
Case 3: Wall-mounted in niche	Case 8: Wall-mounted with light-well
	
Case 4: Stand-alone with hedge	Case 9: Stand-alone with light-well
	
Case 5: Roof-mounted flat roof	Case 10: Wall-mounted second floor

In the shadow, OF is emerging slowly, mainly in the field of research. Although OF is not user-friendly, it provides full access to the solvers and provides an opportunity to develop your own solvers, boundary conditions, and whatnot. In the present research, a solver called rhoReactingBuoyantFoam is slightly modified to suit the current simulation case and named rhoDyMbuoyantFoam. For preparing the geometry, open-source software called Salome is used. Salome provides a platform for pre- and post-processing for numerical simulation. On further, for post-processing results from OF, an open-source package called Paraview is used.

5.2.3.2 Setup of the simulations

Ten cases were defined in cooperation with manufacturers to identify neuralgic situations that could occur through installation locations and/or distances between neighbor properties or borders to publish space that could surround a house completely or partially, see Table 5-1. Each of these cases got its own mesh convergence study in case its reusage led to physically incorrect setups.

Starting/boundary conditions were defined for each case, but these parameters are quite similar between each other. For this reason, Table 5-2 only provides an insight in these parameters. Each case is simulated eight times resulting in 80 simulations each with isopleth calculations for 25%, 50%, 75%, and 100% with results into 320 3-dimensional isopleth surfaces. These clouds will be reusable for validation measures and to study specific issues if there are any from manufacturers' side.

Table 5-2: Exemplary presentation of case-specific starting or boundary conditions.

S.No	case	$\dot{m}$ (g/s)	wind velocity (m/s)	wind direction
1	case 1	0.6	0.5	xmin
2	case 1	0.6	0.5	ymin
3	case 1	0.6	5	xmin
4	case 1	0.6	5	ymin
5	case 1	5	0.5	xmin
6	case 1	5	0.5	ymin
7	case 1	5	5	xmin
8	case 1	5	5	ymin

5.2.3.3 Results

An exemplary result is how the cloud-building process behaves differently depending on the flow resistances within the free flow conditions outside the unit. A comparison of two similar cases is presented in Figure 5-11. The green isopleth line being projected on the ground is defined as the completely free flow field only influenced by the wind of the outflow conditions (case 2) and the simulated hedge (case 4).

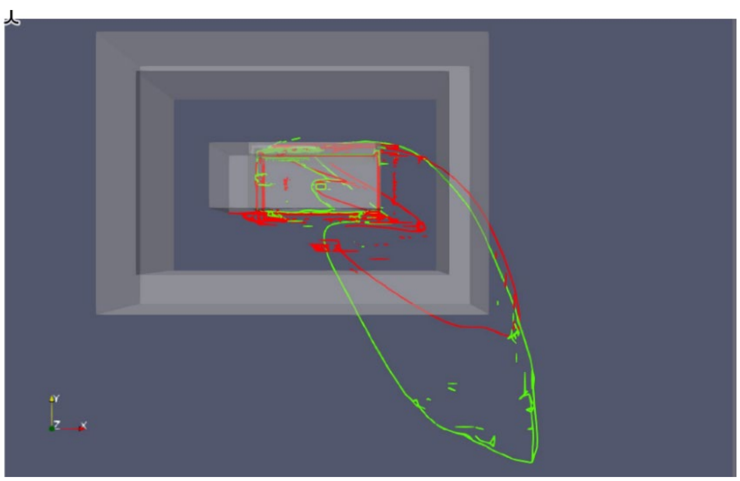


Figure 5-11: Comparison of the 25% LFL ground-projected isopleth lines. Here, cases 2 (green) and 4 (red) are compared to each other to show the difference a flow resistance like a hedge is causing to the cloud-building process.

5.2.3.4 Conclusions and outlook

Simulations were set up to support the development activities of interested manufacturers of A3 outdoor monobloc air-to-water heat pump development. The work is ongoing and will end up with several dozens of 3D-clouds. These data could either be used directly to interpret distribution/outflow effects or to set up experiments. Based on these simulated findings, any gas warning sensor matrix could be arranged much better spatially. Validation work is planned to solidify the reliability of these results.

5.2.4 References

[1] Mittapalli, N., "Numerical Simulation of Leakage and Dispersion of Refrigerant using OpenFOAM", Master Thesis, Hochschule Stralsund.

[2] B. Minor, D. Herrmann, and R. Gravell. "Flammability characteristics of HFO-1234yf". In: Process Safety Progress 29.2 (2010), pp. 150–154.

[3] L. Jia, W. Jin, and Y. Zhang. "Analysis of indoor environment safety with R32 leaking from a running air conditioner". In: Procedia Engineering 121 (2015), pp. 1605–1612.

[4] B. Goetzler, M. Guernsey, S. Faltermeier, and M. Droesch. "AHRI Project No. 8016: Risk Assessment of Class 2L Refrigerants in Commercial Rooftop Units". In: Prepared for Air-Conditioning, Heating and Refrigeration Institute by Navigant Consulting, Inc (2016).

[5] S. Kondo, K. Takizawa, A. Takahashi, K. Tokuhashi, J. Mizukado, and A. Sekiya. "Flammability limits of olefinic and saturated fluoro-compounds". In: Journal of hazardous materials 171.1-3 (2009), pp. 613–618.

5.2.5 Availability of components

5.2.5.1 The compressor

F-Gas compressors for heat pumps are already widely available. Shortages in getting approved compressors for specific F-Gases have almost ended. The newest patented blends, especially of the azeotropic R-5XX series, might have such shortages in the near future.

However, the choice for relevant compressors is usually made in-between 4-6 manufacturers (in terms of economically meaningful specifications). More and more compressor manufacturers have designed their own R290 models, too, and introduced it to the market, see Figure 5-12 for a typical operation envelope.

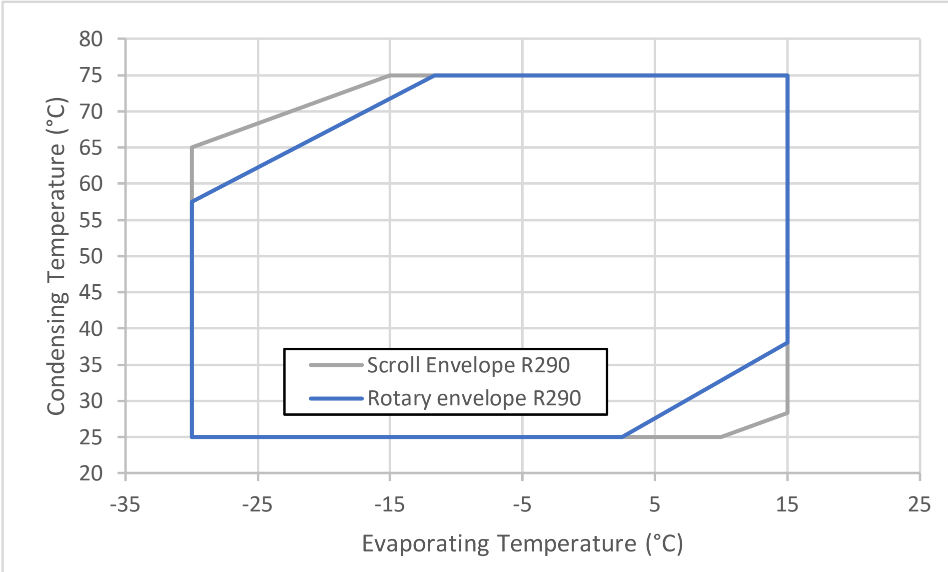


Figure 5-12: Operation envelope (related to heat pump operation conditions) of R290 for available rotary and scroll compressor.[1] Only valid for a definite frequency range.

5.2.5.2 Other components

Not discussed here.

5.2.6 Case Studies

Several R&D stakeholders with any relation in their field of interest in heat pumps were requested to participate with their findings in this task report. We requested and received findings based on new refrigerant-oil investigations for refrigerators and laundry dryers. Below is a short summary of these activities from Fraunhofer ISE and these third parties.

5.2.6.1 Fraunhofer ISE: Short review on experimental evaluation of a charge-reduced heat pump module using 150 g R290

5.2.6.1.1 Introduction

At Fraunhofer ISE, between 2018 and 2020, a low refrigerant charge brine-to-water heat pump circuit was evaluated. The aim of the presented work is to create a heat pump using commercially available components that achieve only 5 to 10 kW heating capacity with a maximum charge of 150 g propane. The following pages will show the first results of a charge-reduced brine-to-water propane heat pump.

Propane is a natural refrigerant and has a low GWP (3) and attractive thermodynamic properties. Due to safety aspects, the refrigerant charge was limited to 150 g, resulting in 0.45 kg of CO_2 equivalent.

5.2.6.1.2 Experimental setup

The reduction of charge was achieved by minimized volumes of the internal components: the condenser and evaporator were chosen with an asymmetric plate profile, the liquid line was

[1] Meaningful excerpt from the manufacturer's approved operation envelope for scroll and rotary compressor.

designed as short and thin as possible, the filter dryer in the liquid line was shifted to the suction line, and the amount of compressor oil was reduced to its minimum. With dimensions of roughly 700 x 500 x 200 mm, the refrigeration circuit is small in comparison to other units with the same capacity. The following table gives an overview of the typical characteristics of the main components used in four different modules. The headline indicates the version number and the inner volume of the modules.

Table 5-3: Survey on the different tested cycle setups.

Version no./ volume	**V 1.0 [4,1 l]**	**V 2.5 [3,6 l]**	**V 2.6 [3,8 l]**	**V 3.0 [4,7 l]**
Compressor	Scroll Manufacturer 1	Rotary v1 Manufacturer 2	Rotary v1 Manufacturer 2	Rotary v1 Manufacturer 2
Condenser	Long Asymmetric 16 Plates	Long Asymmetric 16 Plates	Short Asymmetric 38 Plates	Short Asymmetric 46 Plates
Evaporator	Long Asymmetric 16 Plates	Long Asymmetric 16 Plates	Long Symmetric 16 Plates	Long Symmetric 28 Plates
Piping	Pipes v1	Pipes v1	Pipes v1	Pipes v2

The charge-reduced heat pump circuit was tested at various points of operation. Most measurements were taken in a setup in which the charge was varied. The temperatures for the secondary circuits were chosen based on typical test parameters in the heat pump sector. For the source temperature -10 °C, -7 °C, 0 °C, 12 °C were evaluated. These values refer to the inlet temperature of the evaporator. For the sink 35 °C, 45 °C, 55 °C and 65 °C were chosen as outlet temperatures of the condenser. For both secondary hydraulic circuits, a constant temperature difference between the inlet and outlet of 5K and 3K, respectively, was maintained as specified in EN14511.

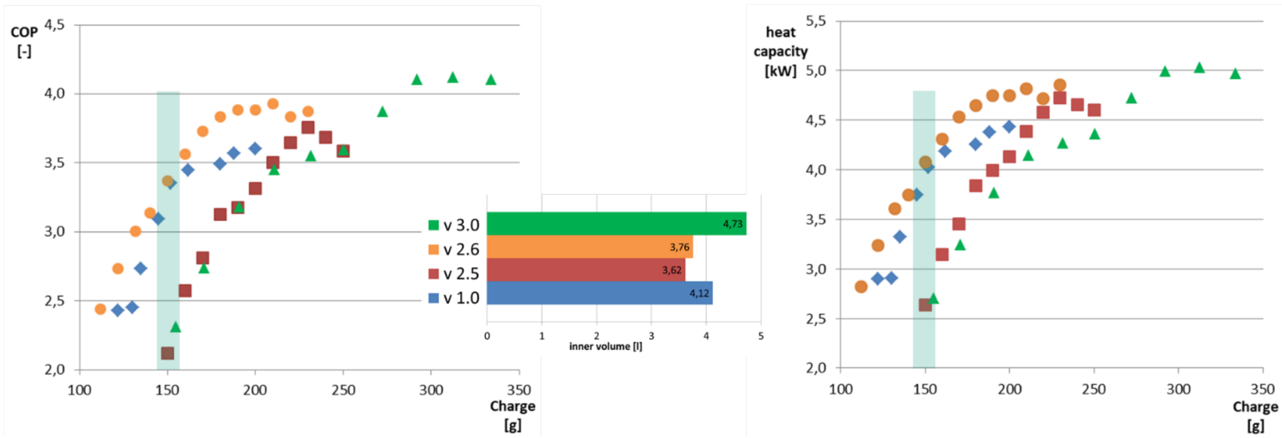


Figure 5-13: COP (left) and heating capacity (right) as a function of refrigerant charge for four different versions of heat pump modules. Results are shown for B0/W35 (brine at evaporator with an inlet temperature of 0 °C, water at the condenser with an inlet temperature of 35 °C), a compressor speed of 60 Hz and a superheat of 10 K.

The total range tested of the compressors was from 30 Hz to 120 Hz in 10 Hz increments. The suction superheat (SSH) has been set to 10 K; nevertheless, it was not reached for all operation points due to the limited operational window of the electronic expansion valve (EEV).

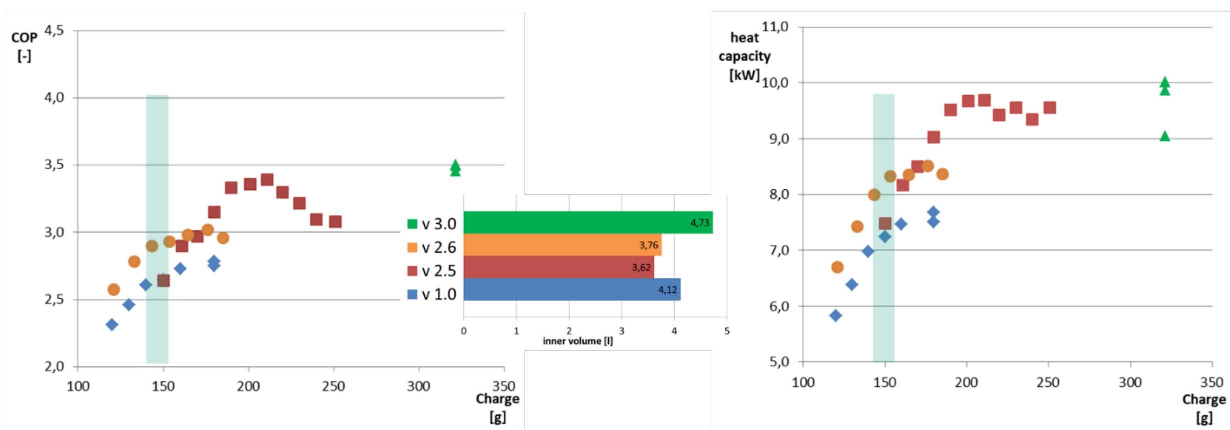


Figure 5-14: COP (left) and heating capacity (right) as a function of refrigerant charge for four different versions of heat pump modules. Results are shown for B0/W35 (brine at evaporator with an inlet temperature of 0 °C, water at the condenser with an inlet temperature of 35 °C), a compressor speed of 120 Hz and a superheat of 10 K.

Increasing the compressor speed to 120 Hz results in an increased heating capacity of 8.4 kW at 150 g and 10 kW in maximum. The COP reaches 2.9 at 150 g and 3.5 in maximum.

Figure 5-13 and Figure 5-14 show an extraction of the results for B0/W35 (brine at evaporator with an inlet temperature of 0 °C, water at the condenser with an inlet temperature of 35 °C), a compressor speed of 60 and 120 Hz and a superheat of 10K. The left graph shows the COP for the different versions, and the right shows the heating capacity, both as a function of the refrigerant charge of the module.

For the mentioned conditions and 150 g of refrigerant charge a COP of 3.4 and a heating capacity of 4 are realized. The maximum COP and heating capacity are 4.1 (COP) and 5 (heating capacity) at higher amounts of charge.

5.2.6.1.3 Discussion

The results generally show the feasibility of a heating capacity of 8 kW with 150 g of refrigerant charge. Additionally, the sensitivity of the charge-reduced system and the strong influence of the components chosen become visible. Optical analyses indicate the maldistribution of the refrigerant in the heat exchangers.

5.2.6.1.4 Outlook

The promising results are the starting point for the project “LC150” (10/2020 – 03/2023), funded by the German Ministry of Economic Affairs and Energy and a European Heat Pump manufacturer. The main goal of this project is the development of a charge-reduced heat pump module and an adapted operation strategy realizing a COP > 4 with a heating capacity > 8 kW. This will be worked out by a broad experimental campaign supported by simulations.

Component manufacturers support the project by supplying heat exchangers, compressors, etc. The heat pump manufacturer and scientific partners such as UPV supervise the work.

5.2.6.2 RWTH Aachen: Systematic application of the decision-making process for the fluid selection of natural refrigerants in heat pumps

5.2.6.2.1 Short description

Vering [1] developed a methodology for the selection process of refrigerants. This multi-criteria process allows the inclusion of all refrigerants that might fit well to an appliance. Vering defines several scenarios and can use a GUI-based human interface for this tool. Integral decision processes were introduced. Vering concludes in his paper that hydrocarbons will play a greater role in future applications. The decision-making process to arrive at such a judgement is not disclosed in the presentation but might be obviously part of the implemented algorithms. However, a better understanding is possible considering his other work on this [2]. His next steps are to make such a tool more robust for decision-making processes. In a final step Vering wants to conduct this survey with different stakeholders to arrive at more accurate results.

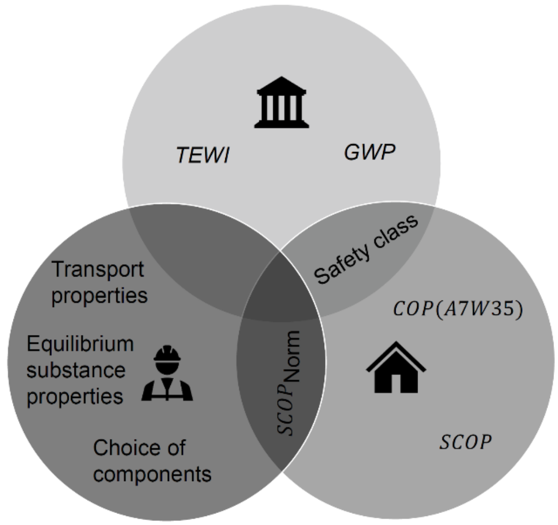


Figure 5-15: Interdependency of stakeholder's interests and their goals.

5.2.6.2.2 References

[1] C. Vering, „Systematic application of the decision-making process for the fluid selection of natural refrigerants in heat pumps," Proceesings of the IIR Gustav Lorenzen Conference, 2020.

[2] C. Vering, H. Kroppa, S. Gansen, D. Müller, „Systematische Anwendung des Entscheidungsprozesses zur Arbeitsmittelauswahl für Wärmepumpen, Forschung im Ingenieurwesen, 2020, DOI: https://doi.org/10.1007/s10010-020-00429-8

5.2.6.3 Technical University Braunschweig: Low-GWP refrigerants for use in small commercial tumble dryers

5.2.6.3.1 Introduction

In household heat pump tumble dryers, the commonly used refrigerant R134a has a high global warming potential and is nowadays replaced by natural refrigerant R290. Commercial tumble dryers demand short drying time and require high heating power and, thus, higher loads of refrigerant. Therefore, their environmental impact per dryer is even bigger compared to the household appliance. R290 and R744 are both valid alternatives for R134a in heat pump dryers [1] [2], with advantages like the low GWP but also some disadvantages. R290 has almost similar thermodynamic properties compared to R134a. Still, it is flammable, and heat pump dryers with higher refrigerant loads exceeding the 150 g limit require additional safety measures for electronic components and installation conditions [3]. R744 enables high temperatures inside the gas cooler due to the temperature glide and, thus, a short drying time. However, due to the different thermodynamic behavior, the heat pump components must be completely redesigned [4]. A simulation study was carried out to compare the thermodynamic potential of R290 and R744 with that of R134a.

5.2.6.3.2 Setup

Based on a validated heat pump tumble dryer simulation model [5] some modifications have been made. The refrigerant side heat transfer coefficients of the evaporator, gas cooler, and cooler were held constant in the simulations for all three refrigerants. The compressor model was exchanged by an efficiency-based model with constant volumetric (0.8) and isentropic efficiency (0.6) to have equal preconditions for every refrigerant. The compressor displacement was set to 6.75 cm² for R290 and R134a and 3.26 cm² for R744. The adjusted simulation model was used in a Pareto optimization varying compressor speed, refrigerant mass, and expansion valve area by using the algorithm MOEA/D [6] and a starting population of fifty randomly distributed individuals. The objectives were both low energy consumption and drying time.

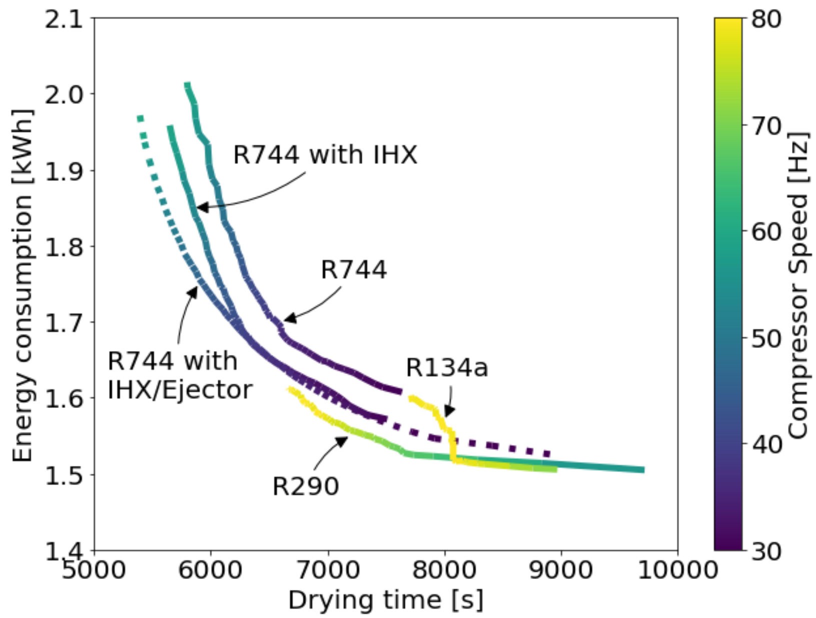


Figure 5-16: Result of Pareto optimization with objectives being energy consumption and drying time. Refrigerant R134a is compared with R290 and R744. For R744, additional system topologies have been investigated: additional internal heat exchanger and combination of ejector, separator, and internal heat exchanger.

As boundary conditions, the compressor outlet temperature must not exceed 100°C during the whole drying cycle, and a superheat below 1 K was always avoided. The boundary conditions were implemented as a penalty function inside the simulation environment. The results of the Pareto optimization with the three different refrigerants are shown in Figure 5-16. Each optimization case results in a Pareto front comprising fifty Pareto optimal solutions for energy consumption and drying time.

5.2.6.3.3 Discussion

As expected, a short drying time goes along with higher energy consumption, and vice versa. A lower energy consumption is only possible with a slower drying speed. The differences between R134a and R290 at slow compressor speed are rather small. With R134a, slightly less energy is consumed, but there is a turning point at higher compressor speed where faster drying speed is only possible at the cost of a considerably higher energy consumption. With the same compressor displacement, a lower speed is needed to achieve the same drying velocity with R290 compared to R134a. That can be explained by the higher volumetric cooling capacity of R290. R744 again has an even higher volumetric cooling capacity and that's why shorter drying times are more easily accessible with low compressor speed. However, in comparison with R290, the energy consumption at equal drying time is higher. One reason for that is the bigger throttling losses caused by the high-pressure difference. To account for this effect, the topology of the heat pump can be altered. Two different topologies were also optimized and compared to the other Pareto fronts in Figure 5-16. With an internal heat exchanger between the evaporator and compressor on the low-pressure side and between the gas cooler and cooler on the high-pressure side, energy consumption can be reduced significantly. The difference between the Pareto fronts of R290 and R744 gets smaller. A combination of ejector, separator, and internal heat exchanger has additional advantages when the aim is to achieve a small drying time. Also, lower energy consumption with the same compressor speed is possible.

5.2.6.3.4 Conclusions

In conclusion, both refrigerants, R290 and R744, are possible replacements for R134a. R290 is favorable when a small energy consumption is desired, and the refrigerant limit of 150 g can be adhered to. R744 has the advantage when there is demand for short drying times. However, the heat pump topology must be adjusted to compete with R290 efficiency-wise.

5.2.6.3.5 References

[1] A. Möhlenkamp, M. Bockholt, N. Brandt, W. Tegethoff and J. Köhler, "Energetische Einordnung des Kältemittels R290 für Wäschetrockner," 2019.

[2] T. Alpögger, "Untersuchung von alternativen umweltfreundlichen Wäschetrocknertechnologien," DBU AZ 31753, TU Braunschweig.

[3] IEC, "Amendment 2 - Household and similar electrical appliances - Safety - Part 2-11: Particular requirements for tumble dryers.," *IEC 60335-2-11:2008/AMD2:2015,.*

[4] T. Alpögger, M. Bockholt and R. Bußmann, "Optimierung eines Kleingewerbe-Wäschetrockners mit CO2-Wärmepumpe," in *DKV Tagung*, Kassel, 2016.

[5] N. Brandt, T. Alpögger, W. Tegethoff, M. Bockholt, A. Möhlenkamp and J. Köhler, "Exergetic analysis of different R744 heat pump tumble dryer system topologies," *Applied Thermal Engineering,* no. 161, 2019.

[6] Q. Zhang and H. Li, "MOEA/D: A Multiobjective Evolutionary Algorithm Based on Decomposition," *IEEE Transactions on Evolutionary Computation, doi: 10.1109/TEVC.2007.892759,* 2007.

5.2.6.4 Technical University Dresden: Work on lubricants for heat pump laundry dryers and refrigerators

5.2.6.4.1 Short introduction

Nosbers et al. [1] and Stöckel et al. [2] investigated a zeotropic mixture out of R-290 and R-E-170 (dimethylether) with a focus on the determination of the experimental refrigerant-oil mixture behavior of this ternary system. At first, the pure refrigerants were tested together with the lubricant. In Figure 5-17 and Figure 5-18, the test apparatus, as well as the results of the pure refrigerants with the oil, are presented.

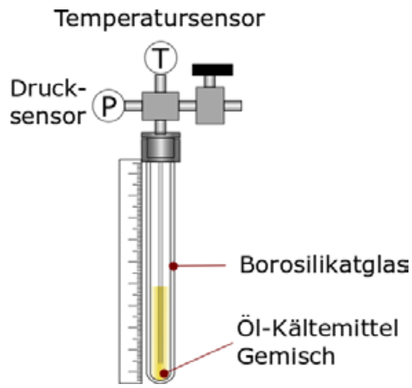


Figure 5-17: Apparatus for the measurement of the phase equilibrium thermodynamics.

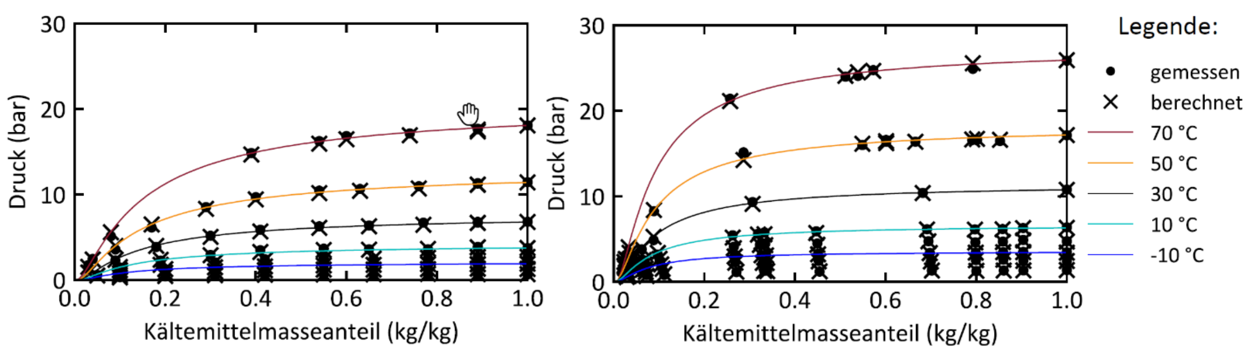


Figure 5-18: Measured values and values calculated via data fit for refrigerant mass fractions from 0 to 1 kg kg-1 left: for POE + DME, right: for POE + propane

5.2.6.4.2 Conclusions

The measurement and calculation results indicate that the selected approach is a suitable tool for determining the solubility of individual refrigerants in oil. Here, the average deviation between the measured and theoretically calculated values of the exemplarily selected binary refrigerant-oil mixture with R290 is 5.85% of the binary mixture with RE170 4.10 %. A notable drawback of the presented equation is the necessary knowledge of the molar mass of the oil, which may not be known. This is especially true for mineral oil-based lubricants, which usually consist of many different hydrocarbon chains (naphtenes). However, consideration of the results for various assumed molar masses of the measurements described in this manuscript shows that the influence of the molar mass is sufficiently small.

5.2.6.4.3 References

[1] Ramona Nosbers, Katharina Stöckel, Christiane Thomas, Ullrich Hesse, "Experimentelle Untersuchung von Kältemittel-Öl-Gemischen für die Anwendung in Haushaltsgeräten", DKV, Proceedings of the Annual Meeting 2020.

[2] Katharina Stöckel, Ramona Nosbers, Christiane Thomas, Ullrich Hesse, “Experimentelle Analyse eines Schmiermittels für Kohlenwasserstoff-Kältemittelgemische”, DKV, Proceedings of the Annual Meeting 2020.

5.2.7 Conclusions

There are plenty of options on the one side for HFOs and on the other side for A3 refrigerants available. Due to the work in WG12 of the CEN/TC 182 in Europe, certain barriers on the normative side are reduced for the usage of A3 refrigerants. Based on this and with a view on the demonstration as well as development activities in Germany (from manufacturers, R&D service providers, and Universities) – as partially described above – the introduction of low-GWP and very low-GWP refrigerants is on its way. Safety aspects, as analyzed deeply for A2L refrigerants from several nations and researchers, were intensified and will result in better background information when safety aspects for A3 systems are addressed. More types and manufacturers are expected to come up with A3 but also A2L solutions for their new developments.

5.3 Review of state-of-the-art technologies in 2021

Prepared by:

Thore Oltersdorf[1]*, Lena Schnabel[1], Simon Braungardt[1], Hannes Fugmann[1], Peter Schossig[1], Jeannette Wapler[1]

[1]Fraunhofer Institute for Solar Energy Systems (ISE), Department Heating and Cooling Technologies, Freiburg, Baden-Wurttemberg, Germany

January, 2022

*** Corresponding Author, Thore Oltersdorf (thore.oltersdorf@ise.fraunhofer.de)**

5.3.1 Introduction

This is the continuation of the German contribution to the Annex 54 Annual Report 2020[1] included a summary of the most recent large-scale heat pump monitoring project, “WP Smart im Bestand”[2] (FKZ 03ET1272A) at Fraunhofer ISE, a review of ongoing heat pump projects in Germany based on an analysis of the enArgus database (www.enargus.de) and a survey on heat pumps and their refrigerants as part of the market incentive program (MAP) coordinated at the Federal Office for Economic Affairs and Export Control (BAFA).

Since the monitoring project has ended and the enArgus database can easily be accessed by anyone to get an overview of the most recent public, innovative heat pump projects, only the analysis of state-of-the-art heat pumps on the German and EU market is analyzed, updated, and extended in this report.

5.3.2 State-of-the-art on currently market-available air-to-water heat pumps

This year, the top-down approach to analyzing market-available heat pumps to identify current components and system designs using already low-GWP refrigerants was put into focus, extended, compared to last year’s activities, and comprises now.

1. An update of BAFA heat pump models correlated with their used refrigerants. This time, the dataset doesn’t focus only on the ten largest manufacturers. This year, the coverage of identified refrigerant type was 83% out of about 2650 listed air-to-water heat pumps.

---

[1] https://heatpumpingtechnologies.org/annex54/wp-content/uploads/sites/63/2021/09/iea-annext-54-annual-report-020121.pdf

[2] See here: https://www.ise.fraunhofer.de/en/research-projects/wpsmart-im-bestand-heat-pump-field-trial-focus-existing-buildings-and-smart-control.html

The used version for the BAFA list was from 14th December 2020 as the last version offered, including COP data,

2. The analysis of sold heat pumps (only models included in the incentive scheme) within 2019 in terms of the used refrigerants with coverage of >99% identified refrigerants of all sold heat pumps and
3. The analysis of all medium-temperature air-to-water heat pumps listed as part of the HP key mark database.[1] This provides similar, if not even better, data on market available systems due to the large number of dead bodies in the BAFA list of subsidized heat pump models.[2]

5.3.3 Analysis of the BAFA database

The combination of different data sources continues to correlate the refrigerant types as well as the COPs within the BAFA dataset. The BAFA dataset used this time is the last version available, including COP figures, and is from 14th December 2020. Only air-to-water heat pumps were analyzed. BAFA data included up to four different COPs for air-to-water heat pumps. It is assumed that the largest share of the listed COP figures is based on testing heat pumps according to DIN EN 14511 and DIN EN 14825. Contrary to the analysis in the Annex 54 annual report in 2020, this analysis was not limited to the largest manufacturers but aimed to maximize the amount of heat pump models for which the refrigerant type could be identified, see Figure 5-9 for the graphical representation of this analysis. There were 13 different refrigerants identified. A relatively large share of 744 units is still not identified in terms of the used refrigerant types since online data on the heat pump specifications were investigated. The error bars represent a scattered range of available heat pumps for a specific refrigerant. Of course, the more heat pump models are offered, and the longer a refrigerant is used in market-available systems, the broader these error bars become. This is due to a change in the technical readiness of such systems (old systems are also included in these figures) and quality differences between manufacturers and their models.

Peaks and Minima represent individual models defining these limits. These limits could be surprisingly small or large. If possible, the dataset was analyzed to avoid such broadening effects of the scatter ranges due to typos in the BAFA list entries.

To simplify the comparison of the future-proof low-GWP refrigerants included in the BAFA database Figure 5-10 and Figure 5-21 show a comparison limited to the low-GWP refrigerants.

[1] See here: https://www.heatpumpkeymark.com/ (last visit: 15th December 2021)

[2] For comparison have a look to the most recent BAFA “list” here: https://www.bafa.de/SharedDocs/Downloads/DE/Energie/ee_waermepumpen_anlagenliste_bis_2020.pdf?__blob=publicationFile&v=1 (last visit 15th December 2021)

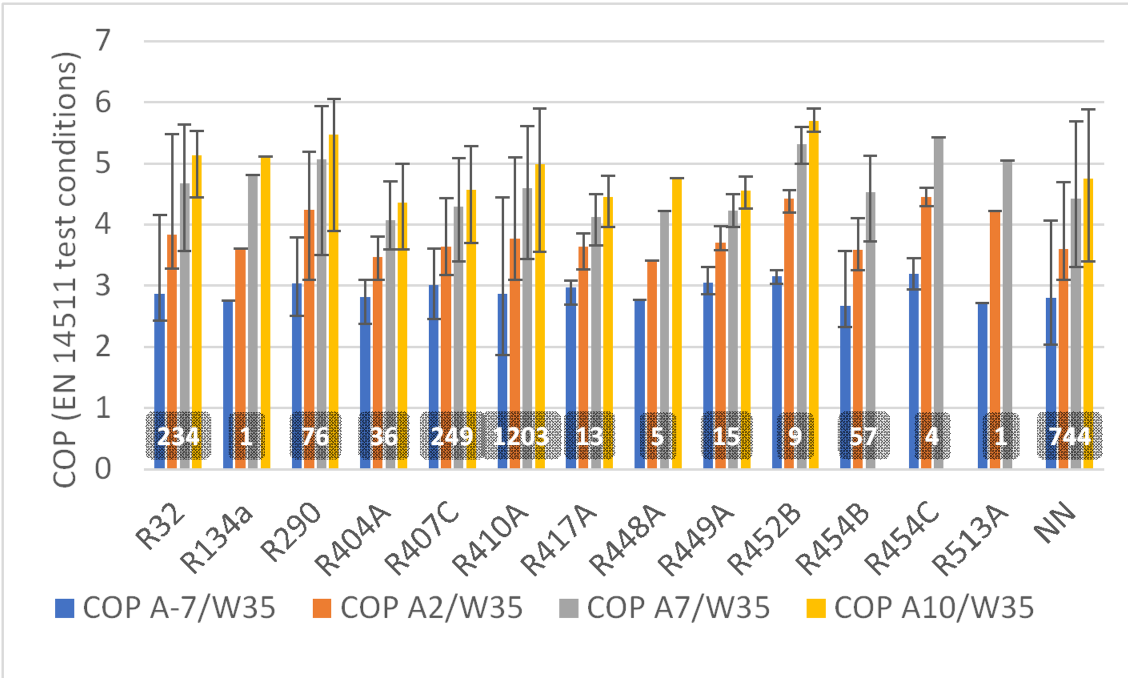


Figure 5-19: Refrigerant-specific graphical representation of the COP values included in the BAFA tables in 12/2020 for air-to-water heat pumps.

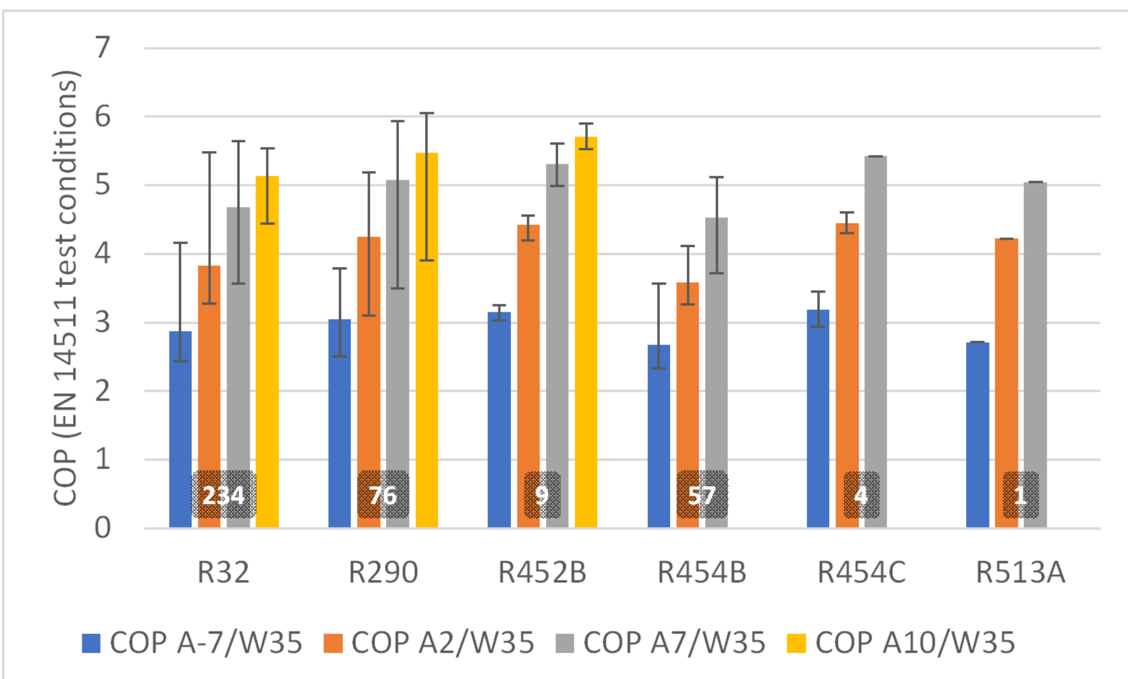


Figure 5-20: Refrigerant-specific graphical representation of the COP values included in the BAFA list in December 2020 for air-to-water heat pumps, filtered to focus only on low-GWP refrigerants. The GWP-threshold was set to the GWP of R32.

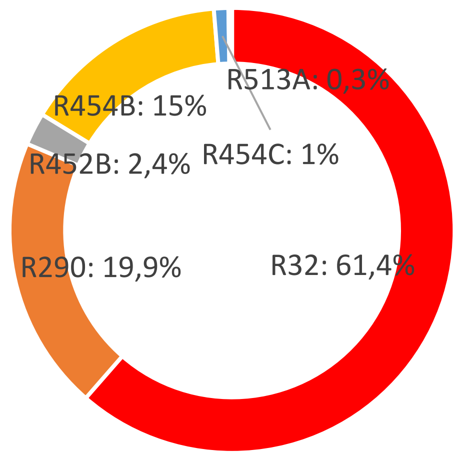


Figure 5-21: Share of low-GWP refrigerant (neglecting the large amount of not identified refrigerants; see NN in Figure 5-9). The GWP threshold was set to the GWP of R32.

5.3.4 Analysis of sold units of the German funding schemes MAP and BEG

The BAFA lists have been published for more than ten years now. Due to the unreviewed character of this list, it contains a share of dead bodies for which heat pump specifications can still be found, but which are not offered on the market anymore. Furthermore, sales figures are not equally distributed over all listed heat pump models. For this reason, the share of refrigerants charged in funded heat pump units within the German funding program differs a lot from the data of the product databases.

Data on funded heat pumps (more than 25.000 units) were correlated to their refrigerants. A coverage of about 99% was reached for the refrigerant identification for the annual figures of funding applications of the MAP for 2019. A Comparison of the shares of refrigerant types is shown in Figure 5-22.

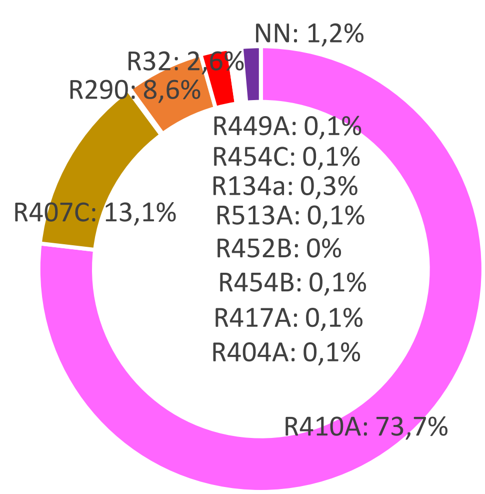


Figure 5-22: Comparison of the shares of refrigerant types. The graph comprises all refrigerant types for air-to-water heat pump units sold in 2019 as part of the market incentive program.

5.3.5 Analysis of the HP Keymark database

To complete the picture of relevant figures about current market-available air-to-water heat pump models, the HP Keymark database was analyzed. HP Keymark is a certification mark. The official Keymark website defines the HP Keymark as cited below:

> "*The Heat Pump KEYMARK is a voluntary, independent European certification mark (ISO type 5 certification) for all heat pumps, combination heat pumps and hot water heaters (as covered by Ecodesign, EU Regulation 813/2013 and 814/2013).*
> *It is based on independent, third-party testing and demonstrates compliance with product requirements as set in the Heat Pump KEYMARK scheme rules and with efficiency requirements as set by Ecodesign Lot 1 and Lot 2.*
> *The Heat Pump KEYMARK scheme is owned by the European Committee for standardization (CEN). The certificates are granted by independent Certification Bodies to products fulfilling all requirements of the scheme.*
> *The scheme is open to all Certification Bodies in Europe. Manufacturers interested in obtaining the certification should apply with one of the empowered Certification Bodies.*"[1]

Once again, the analysis was limited to air-to-water heat pumps. The analysis was further limited to the medium temperature applications, which includes the data for EN 14511-2 testing at the ambient temperature 7°C as well as the two supply temperatures of 35°C (low temperature – LT) and 55°C (medium temperature – MT), respectively, see Figure 5-23. The bar plots show the COP at both operating conditions.

The HP Keymark database is, contrary to the BAFA list, not very old, and thus, it promises to comprise fewer dead bodies than the BAFA database on heat pump models. The HP Keymark website was last visited on 28th June 2021 to generate the database and the figures. Similar – as shown for the BAFA data – scatter ranges were included in the bar plots. As before, the scatter range becomes larger the number of included models is, and the longer a refrigerant is established as being used in heat pumps. Peaks and Minima represent individual models defining these limits. These could be surprisingly small or large. If possible, the dataset was analyzed to avoid such broadening effects of the scatter ranges due to typos in the Keymark database entries.

[1] https://keymark.eu/en/products/heatpumps/heat-pumps (last visited 2nd January)

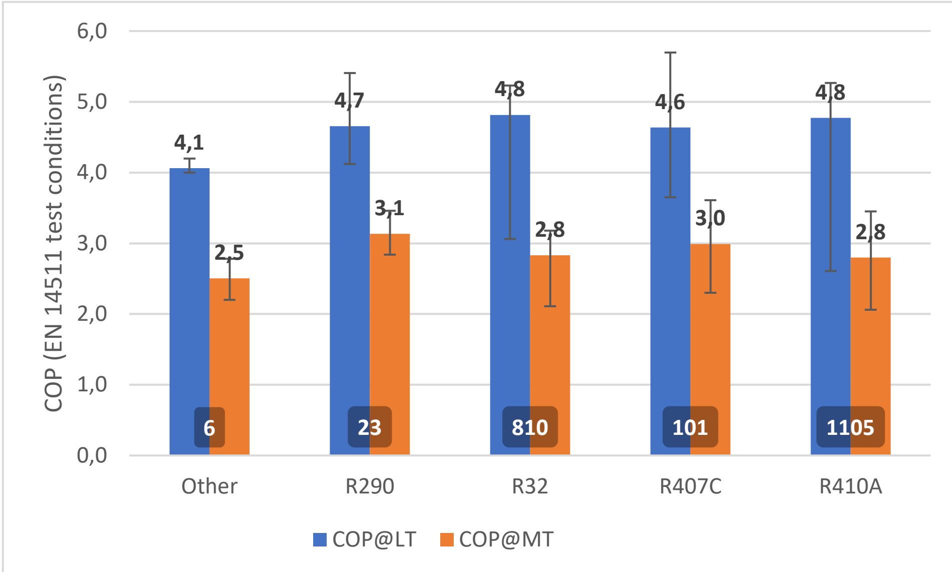


Figure 5-23: Refrigerant-specific graphical representation of the COP values for air-to-water heat pumps included in the HP Keymark database.

5.3.6 Conclusions

Independent from the investigated databases from all available heat pump types in these databases, only air-to-water heat pump types were analyzed due to their large market relevance.

The analysis of market-available heat pumps allows very diverse but also very relevant analysis to understand roll-out processes for newly developed heat pumps based on low-GWP refrigerants and also to understand what efficiencies can be expected for these refrigerants.

It can be concluded that many heat pump models that use future-proof low-GWP refrigerants are already available on the market. In terms of efficiency, heat pumps with low-GWP refrigerants are similar, and differences are at the maximum in the first decimal place.

5.3.7 Outlook

To get optimized energy and emission-saving strategies, it makes sense to investigate the details of these differences. Optimal emission savings could be reached by choosing specific refrigerants. Care must be taken in such a case to include the most efficient and modern heat pumps. Fraunhofer ISE will continue investigating the datasets in 2022 to support Task 3 activities for identifying LCCP reduction potentials.

In addition, a more in-depth analysis of all heat pump models, sorted by the refrigerants used, will be carried out to understand whether key figures such as "technical readiness" or potential for further improvements can be derived.

5.4 Case studies and design guidelines for optimization of components and systems in 2021

Prepared by:

Thore Oltersdorf[1]*, Lena Schnabel[1], Simon Braungardt[1], Hannes Fugmann[1], Lukas Joos[1], Christian Vering[2], Valerius Venzik[2], Christoph Höges[2], Dirk Müller[2], Melanie Cop[3a], Erik Mickoleit[3b], Katharina Stöckel[3a], Riley B. Barta[3a], Andreas Jäger[3b], Ulrich Hesse[3a], Cornelia Breitkopf[3b], Wilhelm Tegethoff[4], Christian Peteranderl[4], Claudia Becker[5], Britta Pätzold[5], Dietram Oppelt[5], Robin Meinert[6], Björn Albertsen[6], Arne Speerforck[6], Gerhard Schmitz[6], Luisa Haak[7], Nico Mirl[7], Johannes Brunder[7], Klaus Spindler[7], Konstantinos Stergiaropoulos[7], Melanie Werner[8], Tobias Reum[8], Mathias Ehrenwirth[8], Christoph Trinkl[8], Tobias Schrag[8]

[1]Fraunhofer Institute for Solar Energy Systems (ISE), Department Heating and Cooling Technologies, Freiburg, Baden-Wurttemberg, Germany

[2]RWTH Aachen, E.ON Energy Research Center (RWTH), Institute for Energy Efficient Buildings and Indoor Climate, Aachen, North Rhine-Westphalia, Germany

[3a,3b]Technical University Dresden (TUD), [3a]Bitzer-Chair of Refrigeration, Cryogenics and Compressor Technology, [3b]Chair of Technical Thermodynamics, Dresden, Saxony, Germany

[4]Technical University Braunschweig (TUB), Institute for Thermodynamics, Braunschweig, Lower Saxony, Germany

[5]HEAT GmbH (HEAT), Königstein, Hessen, Germany

[6]Technical University Hamburg (TUHH), Institute for Thermodynamics, Hamburg, Hamburg, Germany

[7]University of Stuttgart, Institute of Building Energetics, Thermotechnology and Energy Storage (IGTE), Stuttgart, Baden-Wurttemberg, Germany

[8]Technische Hochschule Ingolstadt (THI), Building Energy Technology and Thermodynamics, Ingolstadt, Bavaria, Germany

*** Corresponding Author, Thore Oltersdorf (thore.oltersdorf@ise.fraunhofer.de)**

5.4.1 Summary

The work on heat pump research in Germany in 2021 is diverse and heterogeneous in terms of involved institutions (universities, public research bodies, and companies) and topics. Within the last five years, the activities of heat pump research have changed. The activities cover more fundamental research up to the application of deployable heat pump demonstrators for white goods (e.g., dishwashers), mobile systems for electric-driven buses, or large-capacity heat pump systems for multi-family houses.

5.4.2 Introduction

Main activities in Germany will be introduced as separate cases and can be associated with the following research topics (if there is any working fluid as part of the research focus and not part of the title already, it will be added in brackets). There is no sequence relationship between the list of authors on the first page of the German Task 2 report and the activities listed and described in this section and the following section. Authorship and origin of the work can be traced back by following the abbreviations mentioned for each institution.

- System design principles
  - Towards an integrated design of heat pump systems: Application of process intensification using two-stage optimization (RWTH)
- Piping design
  - Investigation of Pressure Drop & Mass Flow Distribution in Refrigerant Pipes (TUHH, R1234yf)
- Precise charge optimization
  - Automated charge optimization toolchain for LC150 project (ISE, R290)
- Working fluid research
  - Theoretical Assessment of Binary Mixtures as Working Fluids in Heat Pump Cycles (RWTH, binary mixtures of R290, R1270, R600, R600a, R170 and R744 are in the focus)
  - Predictive Screening of Working Fluid Mixtures to Increase the Energy Efficiency of Refrigeration Systems and Heat Pumps (TUD, binary mixtures with a focus on R290, RE170, and other refrigerants are involved)
- System research
  - Networks with lowered temperature as providers of control power (THI, R513A)
- Mobile systems
  - Heating and air conditioning of battery electric city buses by reversible R744 heat pump modules (TUB)
- Stationary systems
  - Hybrid Heat Pump+ research (THI, R454B)
  - LowEx-concepts for supplying heat to existing multifamily buildings – New refrigerants for high-temperature heat pumps (ISE, R454C/R455A)
- Self-driven processes
  - Experimental parameter studies on a two-phase loop thermosyphon cooling system with R1233zd(E) and R1224yd(Z) (TUHH)
- Component-testing research
  - Optimal Designed Experiments for Reliable Model Calibration of a fixed-speed Scroll Compressor with R410A and R32 (RWTH)
- Standard research
  - Domestic heat pumps with natural refrigerants – development of requirements for climate-friendly and energy-efficient appliances for the Blue Angel (HEAT)

- Safety research
  - Main findings of the OpenFOAM CFD simulation study on a monoblock propane heat pump in ten different installation location scenarios (ISE, R290)
- Absorption research with low-GWP refrigerants
  - Efficiency increases of an NH_3/H_2O absorption chiller – Experimental investigation of a plant concept with plate desorber (IGTE)

5.4.3 Case studies

5.4.3.1 Research on system design principles: Towards an integrated design of heat pump systems: Application of process intensification using two-stage optimization (RWTH)

For a sustainable building stock, air-source heat pump systems are identified as a key technology in this work. The authors conclude that there is no integrated strategy to design heat pump systems optimally. The authors use process intensification to simultaneously consider the heat pump system design and operation.

Based on a systematic application of the process intensification regime, the complexity of the optimization problem is reduced by applying rigorous analysis and modeling before optimization. The main conclusions found by the authors are that compared to (typical) HPS design guidelines, the optimal solutions improve costs by up to 36.4% and CO2-equivalent emissions by up to 51.7%. Furthermore, R290 and vapor injection are selected as optimal fluid and flowsheet due to the broader envelope and higher efficiency than all other options (case a). This theoretical framework has not yet been validated/tested for practicality.

5.4.3.2 Piping design: Investigation of pressure drop & mass flow distribution in refrigerant pipes (TUHH)

With the commencement of EU Directive 2006/40/EC, refrigerants with a global warming potential greater than 150 have no longer been permitted in new passenger cars since January 1, 2017. As a result, the widespread refrigerant R134a has been substituted with the low-GWP alternative R1234yf in automotive air conditioning systems. Since the two refrigerants have very similar thermophysical properties, there is no need to redesign the refrigeration cycle. However, the question arises of how the substitution affects the individual system components in detail. In this work, therefore, a comprehensive investigation of the single-phase and two-phase pressure drop of refrigerant lines is carried out. In addition to serially flowed lines, another focus of this work is investigating the hydraulic flow behavior of evaporator tubes connected in parallel. For the experimental determination of the pressure drops and for the validation of the models used, a test facility with the refrigerant R1234yf is set up, which allows the measurement of different line types under the respective usual operating conditions. For the numerical investigation of the geometries, both one-dimensional system simulations and three-dimensional field simulations are carried out.

The investigation is based on simple geometries such as a straight pipe, a 90° bend, an S-bend, and a pipe helix. It is found that the pressure drop of these components in single-phase flows can be calculated very accurately using known correlations from the literature. If the Mach number is greater than 0.18, there is a significant influence of gas compressibility. In the case of two-phase flows, a large number of literature correlations exist with widely varying accuracy. More complex refrigerant lines from a production car are also investigated. These consist of a combination of straight pipes, bends, cross-sectional variations, and flexible hoses. CFD simulations highlight the strong influence of the tube-to-hose transition pieces on the total pressure drop of the line. Their share can be as high as 85 % for lines with two hoses. If the transition pieces are considered separately in the modeling, one-dimensional models are suitable for predicting the pressure drop of the refrigerant line with an error of less than 10 %. A system simulation of the entire refrigeration cycle further shows that the cumulative pressure drop of the lines during operation can be as high as 1 bar. This leads to an overestimation of efficiency by up to 4.9 % if the lines are neglected. The investigation of the hydraulic interaction for two evaporator tubes connected in parallel shows that the heat flow ratio has the strongest influence on the mass flow distribution. In this case, an increase in the heat flow ratio by 10 % points approximately causes a reduction in the mass flow ratio by 10 % points as well. To avoid a cooling failure, the control of the total mass flow, the reduction of the inlet subcooling or the installation of upstream resistances are suitable. It is shown that the mass flow ratio alone is not sufficient to evaluate the cooling, which is why gas superheat must also be considered in the case of complete evaporation.

5.4.3.3 Precise charge optimization: Automated charge optimization toolchain for LC150 project (ISE)

At Fraunhofer ISE, the LC150 project is ongoing in which industrial partners – representing 60% of the German heat pump market – are involved in developing the database for propane-based heat pump appliances for indoor applications. The core activity is a fully automated cross-evaluation; a team from the institute is testing various components of heat pumps on a large scale, in which dozens of component combinations under different operating parameters are investigated. The year 2021 was fully focused on the deployment of automated test benches as well as the optimization of procedural tasks to start the experimental testing campaigns of up to 80 different refrigerant cycles.

The main objectives are to reduce the volume of required refrigerant further, to identify methodological correlations, and to obtain data for the simulation of heat pump design. The measurement campaign collects an abundance of parameter variations 24/7 over one year, thus generating a unique database. The tests run in parallel on three identical test stands 24 hours a day for one year, with between 30 and 150 operating points being measured per prototype and the measured values recorded by 26 sensors. The automated testing technology was developed in close cooperation with the company EP Ehrler Prüftechnik Engineering GmbH.

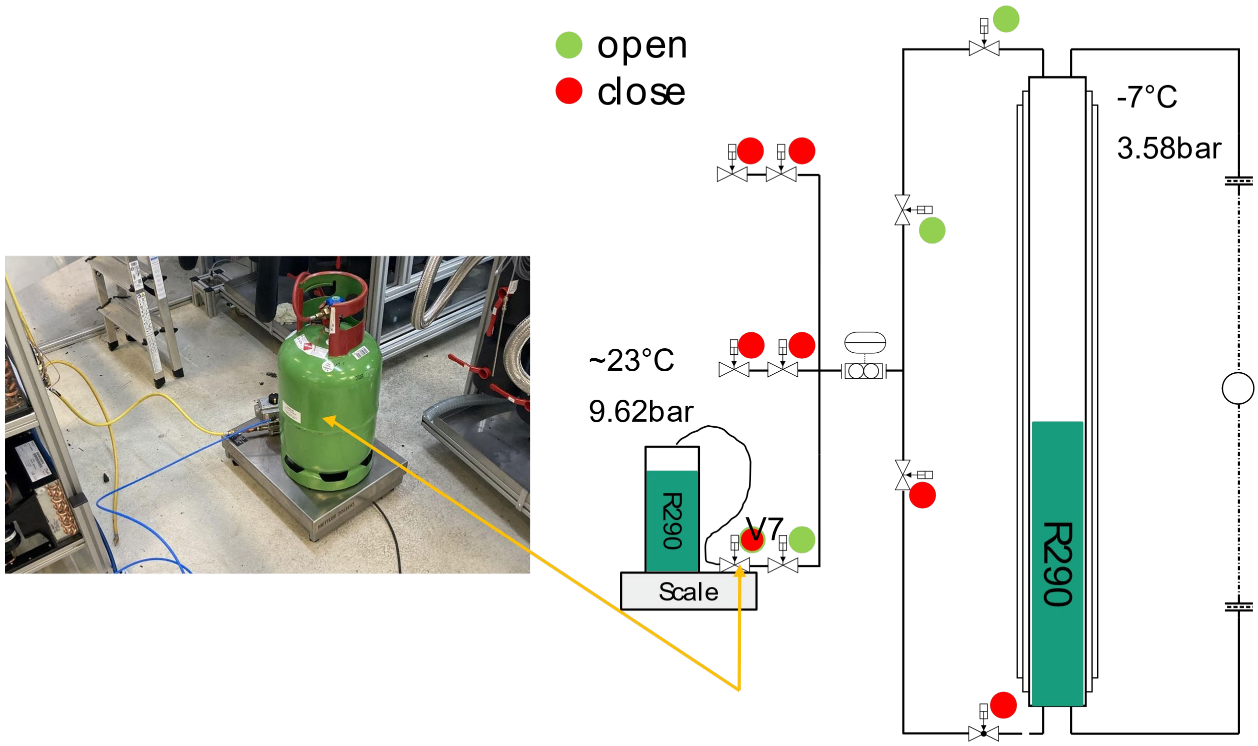


Figure 5-24: Core element of the automated charging equipment: a liquid column in which a high precision dP measurement is realized with several compensation measures to minimize uncertainties

The automated charging equipment, shown in Figure 5-24, allowed in first tests the following reproducible charging and discharging routines, see Table 5-4.

Table 5-4: Reached charge process specifications

Action	dP-Sensor (mass measurement due to liquid column)	Balance (gravimetric mass measurement)	Coriolis (mass measurement by mass flow)
Charging process for 100g refrigerant			
Start at T_{sat} -7°C	0	0	0
V7 closed	101,3	100,7	101,6
Equilibration time 30 min	100,3	100,6	101,6
Equilibration time 90 min	100,4	101	101,6

The needed accuracy is reached after about 30-60 min equilibration time, depending on ambient conditions as well as the handled charge amounts. The operation of this testbench also works at very small refrigerant charge changes. Due to the fully automated testbench and the physical consequences of working with cold traps and not-so-small refrigerant hoses, the testing time is a relatively long time but acceptable in the 24/7 operation mode. This automated charge modification will be realized at three consecutive cycles but in the same testing campaigns. The first results are expected within 2022.

5.4.3.4 Working fluid research: Theoretical assessment of binary mixtures as working fluids in heat pump cycles (RWTH)

In this work, the authors replace conventional refrigerants with zeotropic mixtures. Based on the assumption that zeotropic mixtures have the potential to reduce exergy losses within both heat exchangers, the potential for improvement of the mixture is investigated. The mixture of interests is propane/isobutane. For the cycle evaluation, two types of compressor modeling approaches are used to study the effects of the mixture composition on the compressor. The first model uses a constant isentropic efficiency, while a semi-physical compressor model is used in the second approach, which evaluates the isentropic efficiency for each fluid individually. Both approaches lead to strong deviations. The optimal mixture composition for the first model regarding the cycle efficiency is located at 20 mol-% propane and 80 mol-% isobutane, while the second model results in an optimal composition of 90 mol-% propane and 10 mol-% isobutane. For both studies, efficiency improvements of 4 % to 8 % are possible compared to the existing mixture R436A. The high deviations result from the shifts in isentropic efficiency. Thereby, propane shows the highest, and isobutane shows the lowest isentropic efficiencies using the semi-physical compressor model. The authors conclude that the assumption of a constant isentropic efficiency is inaccurate when variations in mixture compositions are studied. Thus, precise models not only for the heat exchangers but also for the compressor are necessary when working fluids are compared.

5.4.3.5 Working fluid research: Predictive screening of working fluid mixtures to increase the energy efficiency of refrigeration systems and heat pumps (TUD)

Mickoleit et al. (2020) and Stöckel et al. (2021) have presented the application of a new predictive mixture model to identify optimal working fluid mixtures for different cycle architectures, see Jäger et al. (2018a, 2018b). The screening of the working fluids is carried out for specific applications in the corresponding refrigerant circuits with the goals of a GWP below 150 and high efficiency. Figure 5-25 shows preliminary results for a binary mixture screening applied to a heat pump in a dishwasher. The corresponding process schematic is shown in Figure 5-26. The current investigation focuses on validating the thermophysical properties predicted in the mixture model. In the next step, the theoretically most suitable working fluid is tested in an adapted heat pump dishwasher to validate the system-level performance enhancement predictions in addition to the validation of the refrigerant property predictions made by the model.

A commercial dishwasher was equipped with a basic refrigeration cycle to replace the electrical heating element with a refrigerant condenser. A single-speed compressor, an air-cooled evaporator, and an electronic expansion device complete the cycle. The screening for a low-temperature glide mixture resulted in a composition of R290 and RE170 of a molar ratio of 87.1% to 12.9%. This blend has a GWP of 2.99. Especially at high condensing temperatures, the mixture with RE170 theoretically reaches higher COP than pure propane.

Within the scope of the project, the test-setup with additional measuring devices serves the validation of the predicted mixture behavior and aids in understanding the implementation of a heat pump in yet another household appliance.

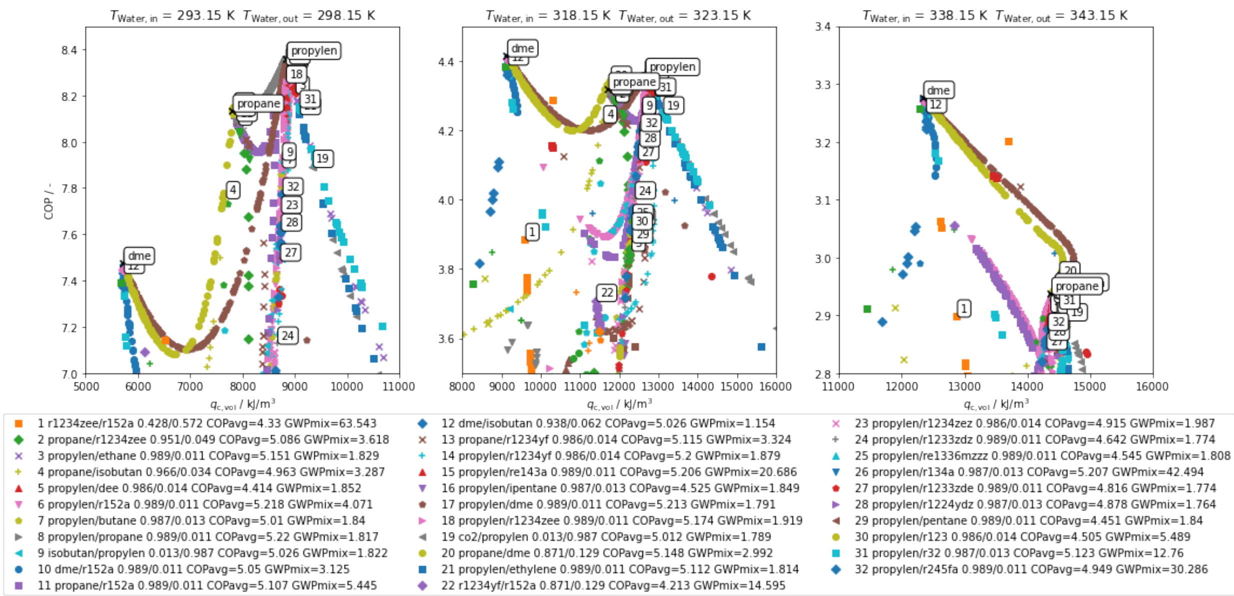


Figure 5-25: Exemplary results (Coefficient of Performance over the volumetric heating capacity) of a binary mixture screening for a dishwasher using a heat pump for supplying water at three different temperature levels.

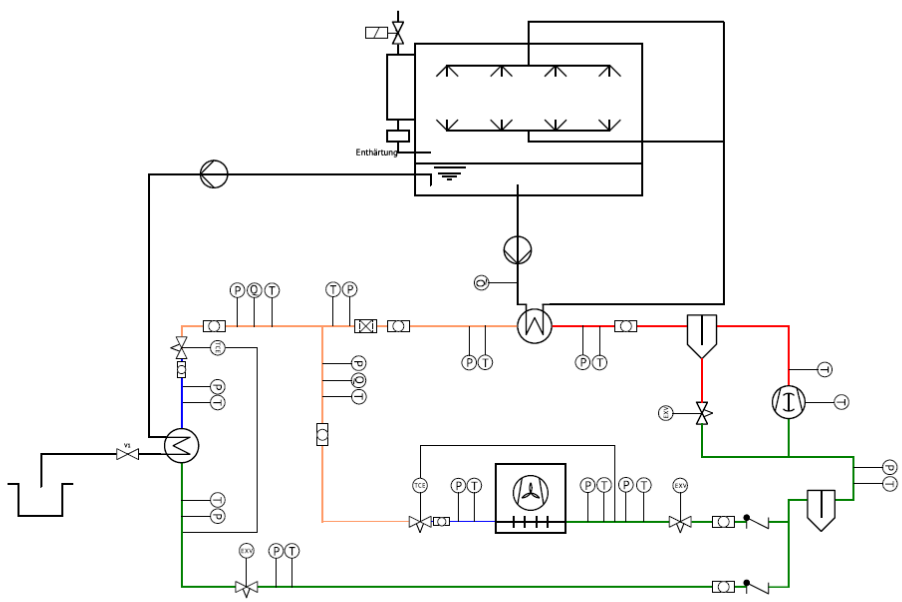


Figure 5-26 : P&I Diagram of the adapted heat pump dishwasher

5.4.3.6 System research: Networks with lowered temperature as providers of control power (THI)

As part of the research project EnEff:Wärme – Networks with lowered temperature as providers of control power (NATAR, FKZ 03ET1425), the use of an alternative refrigerant for decentralized heat pumps was investigated as part of a work package. As part of the project, a heating network in Dollnstein (Bavaria) with seasonal temperature lowering was investigated. The network flow temperature of approx. 45 °C prevailing during the summer months is not sufficient to cover the domestic hot water demand or to meet the associated hygienic requirements. For this reason, in addition to a classic heat exchanger for winter operation, additional decentralized heat pumps with a power range (depending on the consumer) of between 1.9 kW and 3.1 kW are integrated into the consumers' house transfer stations, which raise the heat provided by the grid to the useful temperature level. The decentralized heat pumps are the Oskar-Max product from the manufacturer ratiotherm Heizung + Solartechnik GmbH & Co KG.

Currently, the heat pumps are operated with the refrigerant R134a. To reduce the global warming potential for refrigerant use, tests were carried out by the manufacturer ratiotherm Heizung + Solartechnik GmbH & Co. KG after comparing various refrigerant alternatives with the refrigerant R513A.

The following reasons speak for this choice:

- Reduction of GWP by 50% compared to R134a,
- Identical safety class as R134a,
- No/hardly any constructive changes necessary,
- Expectation of comparable efficiency.

For the testing of the refrigerant R513A, the heat pump was not changed constructively, and the compressor capacity thus continued to range from 25-100 %. For a representative measurement, the source temperature was varied in the range from 10-30 °C and the sink temperature from 35-70 °C. The tests showed that the use of the alternative refrigerant R513A in the heat pump reduces the heating capacity by an average of 1%. In addition, the COP is reduced by 2.2% on average. Based on these findings, it can be concluded that the performance of the heat pump is comparable when using an alternative refrigerant, but the GWP can be significantly reduced compared to R134a.

When using the refrigerant R513A, the expansion valve of the heat pump offers optimization potential. Since the volumetric energy density of the refrigerant is higher, the valve position changes by an average of 15.6 %. Due to the non-linear valve characteristics, a widely closed valve has a detrimental effect on the control behavior. By adjusting the valve, the efficiency of heat pump operation can be improved. Due to the promising results achieved by using the refrigerant R513A and thus reducing the greenhouse potential, further development of the heat pump by ratiotherm is planned in the medium term.

5.4.3.7 Mobile systems: Heating and air conditioning of battery electric city buses by reversible R744 heat pump modules (TUB)

City buses exhibit relatively high energy demands for heating and air conditioning in the passenger cabin compared to other types of vehicles, such as cars or trucks. This is due to the large external area and the frequent door openings. Heating a current battery electric city bus on cold days with ambient temperatures below 0 °C will reduce the driving range by approximately half. For this application, a heat pump can increase the driving range significantly. The currently used refrigerants R134a and R1234yf have limited heating efficiency and are also topics of controversy due to their negative environmental impact. With the natural refrigerant R744 (carbon dioxide, CO_2) these issues are resolved, see Peteranderl et al. (2018) and Peteranderl (2020).

A modular heat pump and air conditioning system make it possible to use passenger car components in a city bus, see Peteranderl et al. (2018). The number of modules can be adapted to customer requirements and the climatic conditions determined for the locally limited areas where city buses are operational. Economies of scale will be achieved by using components from the passenger car industry, see Peteranderl et al. (2018), Peteranderl (2020) and VW (2020).

In the present work of Peteranderl (2020), independent reversible R744 heat pump modules for city buses based on passenger car components are scientifically investigated with regard to the ideal number of modules and energy efficiency. So far, no scientific studies on modular concepts in vehicle HVAC systems are known. In addition, the heating and cooling demands of the cabin in realistic use cases are analyzed, and their minimum is deduced for electric battery city buses. This is used to evaluate the R744 modules.

With the example of a prototype R744 module, the functionality is verified, and measurements are taken to validate a simulation model. The simulation model of the R744 prototype module shows a good correlation to the measurement data. Further optimization steps are implemented in the model, and based on this, the maximum performance is determined, and an energy-efficient control strategy is derived.

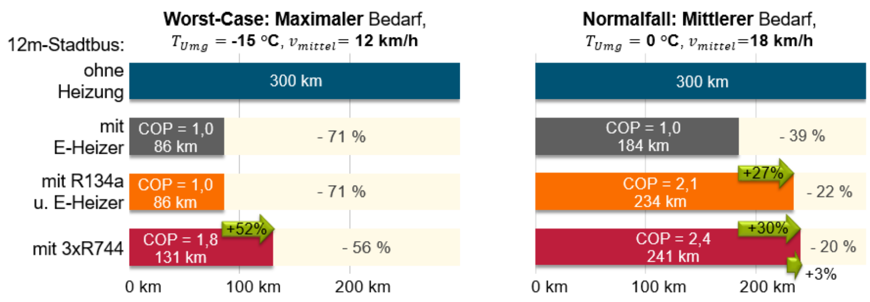


Figure 5-27: Influence of heating technology on the range of a battery-electric city bus

The simulation studies have shown that in heating mode, the active number of modules is reduced at low energy demands to ensure energy-efficient operation. In contrast, in cooling mode, all modules have to be activated. In the reference cities of Munich, Stockholm, Ankara, and Dubai, three modules for heating and cooling a characteristic city bus cabin are required for a typical year of operation. Two modules are needed in Granada and four modules in Moscow. The driving range of a battery electric city bus can be improved in heating mode at -15 °C ambient temperature by up to 52% with three R744 modules compared to an R134a heat pump with an electric heater. The comparison of annual energy consumption in the abovementioned

moderately cold to cold reference cities show 25% of the electric current for heating and air conditioning as well as corresponding ratios of greenhouse gas emissions.

Table 5-5: Comparison of a reference R134a cycle with the investigated R744 cycle performance for different climates

Reference city, climate	Annual savings by a modular R744 mobile air conditioner/heat pump compared to an R134 system
Moskau, very cold	-30 %
Stockholm, cold	-21 %
Munich, gemäßigt	-19 %
Ankara, continental	- 15 %
Granada, warm	- 4 %
Dubai, very warm	+ 27 %

The presented R744 heat pump modules based on passenger car components represent a potential key technology for increasing the efficiency and market share of electric battery city buses for a large part of the world's urban climate regions.

5.4.3.8 Stationary systems: Hybrid heat pump research (THI)

In the current Hybrid Heat Pump+ research project (FKZ: 16KN056420), a new refrigeration circuit connection is being developed that enables flexible and energy-optimized utilization of two different heat sources. By combining, for example, an air-source heat pump with a ground-source heat pump, the individual advantages of the respective heat sources can be utilized in a common refrigeration circuit. This is charged with refrigerant R454B, while components of the heat pump are already largely designed for R32 (the main component of R454B). The COPs achieved in the air source operating mode are like those of an air source heat pump charged with the common refrigerant R410A. In addition to the A2L classification according to ISO 817 (low toxicity and flammability) of the refrigerant R454B, this finding indicates a technically uncomplicated retrofitting with a – compared to conventional refrigerants – significantly low GWP of 467.

Based on the findings, it can be concluded that the use of alternative refrigerants promises comparable performance with a significant simultaneous reduction in greenhouse potential.

5.4.3.9 Stationary systems: LowEx-concepts for supplying heat to existing multifamily buildings – New refrigerants for high-temperature heat pumps (ISE)

The main task of the New Refrigerants for High-Temperature Heat Pumps (NK4HTWP) project was the development of a demonstrator of a heat pump heating system for multi-family houses in existing buildings based on new refrigerants with a sustainable GWP of less than 150. The targeted efficiencies for the heating and hot water operating modes with the operating limit of up to -20°C were met in full, with hot water preparation meeting the requirements of DVGW meets the requirements of DVGW W 551. The plant efficiencies met the project's target of a COP (Coefficient of Performance) of 2.0 for A-7/W55 and reached 2.13, whereby none of the models of comparable size had been offered at the start of the project.

The cost-effectiveness of fan coils was evaluated as an alternative to operating floor heating systems with low flow temperatures. The results show that the annuity of the total costs for systems with fan coils at a supply temperature of temperature of 35 °C compared to a radiator system with a supply temperature of 55 °C is not advantageous.

The vibrations of the refrigeration circuit, as well as noise emissions, could be reduced by extensive work on the ventilation ducting and, with the aid of resonance analyses and the consideration of transfer paths over the pipes, could be identified and reduced.

The construction and operation of a demonstrator were realized in the laboratory and prepared for a field test. The special safety requirements for a new A2L refrigerant were taken into account. Further achievements are shown in Table 5-6.

Table 5-6: Survey on objectives and achievements of the NK4HTWP project

Target:	Target value: What quantitative improvement should be achieved?	Methodology: How should the objective be achieved?
Environmental influences	Improvement of the CO2 balance;	Application of a refrigerant with a GWP < 150. Achieved**.** COP at A-7/W35 > 2.0. **Achieved.**
Costs	Lower costs of the evaporator compared to comparative systems	Cost optimization for components . **Achieved.**
Acoustics	35db(A) in the neighbourhood taking into account tonality allowances. Not yet tested, see report.	Structural dynamic and acoustic investigation of the plant. **Achieved.**
High flow temperature	Energy-optimised compliance with DVGW W 551 for large systems. **Achieved.**	Desuperheater, operational management. **Achieved.**
Minimization of the sink temperature in heating mode	Permanent reduction of the vertical temperature by approx. 2K. **Achieved.**	Design and use of a fan coil unit. **Achieved.**

5.4.3.10 Self-driven processes: Experimental parameter studies on a two-phase loop thermosyphon cooling system with R1233zd(E) and R1224yd(Z) (TUHH)

Two-phase loop thermosyphon (TPLT) is a promising technology looking at highly effective electronics cooling. Due to strong coupling between the internal and external parameters, in this study experimental tests in steady- state are carried out using R1233zd(E) and R1224yd(Z) as a working fluid to investigate the respective influences and resulting design requirements. The relationship between the governing thermal and flow equations is presented to facilitate the interpretation of the test results. The study shows a stable flow and cooling performance over a wide range of heat loads and re-cooling temperatures. The refrigerant charge is identified as one of the main influencing factors, with an optimum being between excessive subcooling and beginning dry-out. Both tested refrigerants lead to basically similar results, showing minor differences regarding thermal performance and system stability.

5.4.3.11 Component-testing research: Optimal designed experiments for reliable model calibration of a fixed-speed scroll compressor with R410A and R32 (RWTH)

A compressor's performance depends on the fluid with its inlet and outlet conditions, an appropriate oil, and the mechanic compression principle. Based on that, the performance is expressed by the isentropic and volumetric efficiency. To describe a compressor in detail and fluid independent is challenging. Therefore, many theoretical studies have been conducted, while in comparison the authors express that experimental studies are rare. To overcome this imbalance, this study focuses a detailed experimental investigation of a 4 kW Copeland scroll compressor with R410A and R32 on a fully automated compressor test stand. Within this paper, the authors present a method for in-depth uncertainty analysis, which ensures the usability and comparability of their experimental results to other experiments. Results are interacting with an optimal experimental design procedure. This allows to reduce experimental effort up to 70 % compared to full factorial experimental designs. To prove the method in a compressor and two fluids, the authors apply it to a fixed-speed scroll compressor with R410A and R32. The test stand can conduct all experiments automatically and part load behavior of both refrigerants can be summarized in a model according to recent Literature with an overall uncertainty below 8 % for R410A. For R32, the method fails. Utilizing this method, the authors aim at open-source experiments in order to accelerate the solution of complex research questions.

5.4.3.12 Standard / Certification research including lifecycle emissions: Domestic heat pumps with natural refrigerants – development of requirements for climate-friendly and energy-efficient appliances for the Blue Angel (HEAT)

Energy-efficient heat pumps, driven by electricity from renewable energies, will be key to achieving carbon neutrality in the building sector. Heat pump sales are increasing strongly. In 2020, 1.62 million units were sold across Europe. 120.000 heat pumps for domestic heating were sold in Germany, where they are already installed in more than half of all newly built houses. Given the huge potential of heat pumps for decarbonizing the building sector and the growing market, the German Environment Agency plans to launch a new Blue Angel ecolabel for heat pumps. The Blue Angel is a well-known, voluntary ecolabel, which aims to help consumers identify the most environmentally friendly products in a certain product group.

Possible criteria for heat pumps are currently being developed by the German consultancy HEAT GmbH as part of the project "Domestic heat pumps with natural refrigerants – development of requirements for climate-friendly and energy-efficient appliances for the Blue Angel". The use of natural refrigerants will be among the criteria. Natural refrigerants are considered the most environmentally friendly option because they have no or very low global warming potential and no harmful atmospheric degradation products. Heat pumps using the natural refrigerant R290 are already well-established in the market, and a growing market share is likely. The emissions caused by the energy consumption of heat pumps during their lifetime represent the most significant environmental impact if the energy is not generated entirely from renewable sources. Therefore, high energy efficiency will be the second crucial criterion.

An interim project report will provide the basis for developing concrete criteria proposals. This report will be published in early 2022. It examines the market and legislative situation, the various available heat pump types on the market with natural refrigerants, and further environmental impacts such as noise emissions.

5.4.3.13 Safety research: Main findings of the OpenFOAM CFD simulation study on a monoblock propane heat pump in ten different installation location scenarios (ISE)

Based on the simulation set-up and the different simulated installation locations presented within the last Annex 54 annual report, major findings are presented. In general, for a risk assessment of externally installed heat pumps with refrigerant propane, it is helpful to estimate the concentration of propane in the vicinity of the heat pump in the event of a leak. The dispersion of propane depends on various factors. Based on flow simulations, the following dependencies of propane dispersion were investigated numerically:

- Location of the heat pump
- Wind speed
- Wind direction
- Leakage mass flow

The simulation results show the dispersion of propane depending on the concentration in the air and in relation to the lower flammability limit (LFL) as a 3-dimensional cloud around the heat pump.

Maximum dispersion of propane can thus be visualized and calculated. The simulation results were checked for plausibility but were not validated with experimental data. A deeper understanding of the R290 dispersion of specific heat pumps with better knowledge of leakage locations, leakage mass flows, and heat pump geometry can only be revealed by individually adapted simulations and measurements. The main and general findings from the general simulation are shown in Figure 5-28.

At medium leakage rates spread 100% LFL predominantly below 1m.

- The lower ignition limit spreads in a large part of the variatione with a distance to the Center of the heat pump out under 1m.
- Exception is an installation of the heat pump in a recess

Rear propane discharge dominant

- The major portion of the propane cloud flows out the back of the heat pump at the evaporator and then exits to the front outside the housing
- Dominant emergence via a hole located in the ground is not evident

Frontal wind speeds less critical

- A frontal wind flow leads predominantly to a smaller dispersion dimension of the propane cloud than (house) parallel flows or flows with the heat pump in the lee of the building.

Propagation LFL at high leakage up to 3m

- High leakage rate of 5 g/s propane and low wind resulted in the largest spread of LFLs of up to 3.5m
- High leakage rates of this magnitude correspond to a "rupture leak". In total, 1.2 kg flows out in 4 minutes.

High wind speed leads to stronger dilution

- the 100% LFL is mostly inside or only a few centimeters outside the heat pump casing at wind speeds of 5 m/s

Figure 5-28: main and general findings of a CFD simulation study of propane dispersion on a monoblock heat pump

A further but less generic analysis specific for each of the ten chosen installation locations is possible but not included here.

5.4.3.14 Absorption research with low-GWP refrigerants: Efficiency increase of a NH3/H2O absorption chiller – Experimental investigation of a plant concept with plate desorber (IGTE)

Absorption chillers and heat pumps use almost exclusively heat as drive energy and are operated with climate-friendly "zero-GWP" refrigerants. At the Institute for Building Energetics, Thermotechnology, and Energy Storage (IGTE), experimental investigations are currently being carried out to increase the efficiency of NH_3/H_2O absorption systems.

A desorber concept was developed with a plate heat exchanger through which the rich solution flows directly. A plate dephlegmator with a downstream condensate separator is used to increase the ammonia mass fraction in the refrigerant. Compared with the widely used desorbers in vessel design with integrated rectification columns, the desorber concept with plate heat exchanger is characterized by a very low filling quantity and low manufacturing costs.

Proof of the high efficiency of the absorption system with plate desorber has already been provided for operation as a heat pump as part of the project "Optimization of Absorption Heat Pumps for Use in the Heat Grid 4.0".

In this paper, newly determined performance data of the direct-flow plate desorber are compared with literature data of a tank desorber in the application case of an absorption chiller. The performance data obtained in the literature are achieved or even exceeded by the new desorber concept.

In the plant concept with plate desorber, no rectification is provided to increase the ammonia content in the vapor, for which only a dephlegmator is used. One challenge in optimizing the plate dephlegmator used to increase the ammonia mass fraction in the refrigerant is the different volume flows of the two fluid streams, refrigerant vapor, and rich solution. Thermographic images are used to analyze the temperature distribution in the plate dephlegmator. To increase the transferred heat flux, a concept for an asymmetric plate dephlegmator is proposed on the one hand, and the orientation of the plate dephlegmator is discussed on the other hand.

5.4.4 Reference

References to Section 5.4.3.1

Vering, C., Stopp, D., Klebig, T., Venzik, V., Müller, D.. Optimal Designed Experiments for Reliable Model Calibration of a fixed-speed Scroll Compressor with R410A and R32. In 2022 IOP Conf. Ser.: Mater. Sci. Eng., Bristol, England, IOP Publishing.

References to Section 5.4.3.3

Fraunhofer ISE LC150 project: https://www.ise.fraunhofer.de/en/research-projects/lc-150.html

References to Section 5.4.3.4

Höges, C., Venzik, V., Müller, D.. Theoretical Assessment of Binary Mixtures as Working Fluids in Heat Pump Cycles. In Proceedings of Ecos 2021 - The 34th International Conference On Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. June 27-July 2, 2021, Taormina, Italy

References to Section 2.1

Vering, C., Wüllhorst, F., Mehrfeld, P., Müller, D.. Towards an integrated design of heat pump systems: Application of process intensification using two-stage optimization. *Energy Conversion and Management,* 250, 114888

References to Section 5.4.3.5

Mickoleit, E., Grau Turuelo, C., Jäger, A., Stöckel, K., Hesse, U., Breitkopf, C., 2021. Screening ternärer Gemische für eine Wärmepumpenanwendung. In Dechema, Proceedings of the Thermodynamisches Kolloquium. Frankfurt am Main, Germany, Dechema.

Stöckel, K., Mickoleit, E., Schaan, L., Grau Turuelo, C., Nosbers, R., Jäger, A., Barta, R., Thomas, C., Breitkopf, C., Hesse, U., 2021. Prädiktives Screening neuartiger Kältemittelgemische mittels TREND und Validierung an einer Wärmepumpen-Geschirrspülmaschine. In DKV, Proceedings of the German Refrigeration and Air Conditioning Conference in Dresden, Hannover, Germany, DKV.

Jäger, A., Bell, I. H., Breitkopf, C., 2018. A theoretically based departure function for multi-fluid mixture models. Fluid Phase Equilib. 469, 56–69. https://doi.org/10.1016/j.fluid.2018.04.015

Jäger, A., Mickoleit, E., Breitkopf, C., 2018. A combination of multi-fluid mixture models with COSMO-SAC. Fluid Phase Equilib. 476, 147–156. https://doi.org/10.1016/j.fluid.2018.08.004

References to Section 5.4.3.7

Peteranderl, C., Bernath, M., Tegethoff, W., Köhler, J., 2018. City bus with modular R744 HVAC system based on passenger car components. In SAE International, Proceedings of the Thermal Management System Symposium (TMSS). Warrendale, Pennsylvania, USA: SAE International

Peteranderl, C., 2020. Heizen und Klimatisieren von batterieelektrischen Stadtbussen durch umschaltbare R744-Wärmepumpenmodule. Braunschweig, Technical University

Volkswagen A. G.. Reichweitenstark: die Wärmepumpe im ID.3, URL: https://www.volkswagen.de/de/elektrofahrzeuge/id-technologie/waermepumpe.html (last visit: 15th January 2022)

References to Section 5.4.3.9

NK4HTWP Project: https://www.ise.fraunhofer.de/de/forschungsprojekte/nk4htwp.html

References to Section 5.4.3.10

Albertsen, B., Schmitz, G.. Experimental parameter studies on a two-phase loop thermosyphon cooling system with R1233zd(E) and R1224yd(Z). International Journal of Refrigeration, 131, pp. 146-156.

References to Section 5.4.3.14

Haak, L., Mirl, N., Brunder, J., Spindler, K., Stergiaropoulos, K., 2021. Efficiency increase of a NH3/H2O absorption chiller – Experimental investigation of a plant concept with plate desorber. In DKV, Proceedings of the German Refrigeration and Air Conditioning Conference in Dresden, Hannover, Germany, DKV.

5.5 Review of state-of-the-art technologies in 2023

Prepared by:

Thore Oltersdorf[1]*, Lena Schnabel[1], Hannes Fugmann[1]

Christian Vering[2], Hannah Romberg[2], Dirk Müller[2]

[1]Fraunhofer Institute for Solar Energy Systems (ISE), Department Heating and Cooling Technologies, Freiburg, Baden-Wurttemberg, Germany

[2]RWTH Aachen, E.ON Energy Research Center (RWTH), Institute for Energy Efficient Buildings and Indoor Climate, Aachen, North Rhine-Westphalia, Germany

*** Corresponding Author, Thore Oltersdorf (thore.oltersdorf@ise.fraunhofer.de)**

5.5.1 Analysis of BAFA data

Based on the analysis of the funded market as presented in previous years below, an updated visualization describes the development of the market continuously from 2016 to 2023.

All market participants (manufacturers, installers and traders) of the funded market were investigated. Overall, about 160-180 market participants were involved.

Below in Figure 5-29 the share of refrigerants of the defined time range is displayed.

The share for the future-proof heat pumps R290 and R32 increased significantly. The dynamics are quite different for both refrigerants and cannot be compared to each other. Some reasons for these dynamics can be seen in the changes in funding schemes in Germany and the roll-out of new heat pump products, see Figure 5-30 shows relevant annual changes.

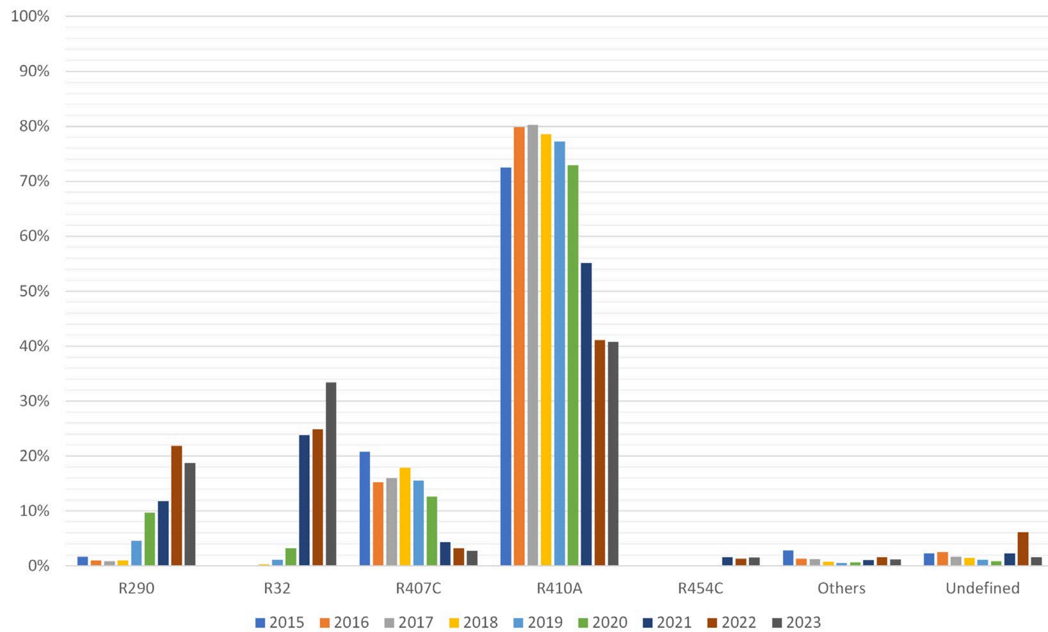


Figure 5-29: Refrigerants being used between 2016 and 2023 in funded heat pump applications.

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 HPs on the (funded) market
2019-2020	-2,9%	-4,3%	+5,2%	+2,1%	Intro of several new R290 HPs on the (funded) market
2020-2021	-8,3%	-17,7%	+2,1%	+20,6%	Intro of new R32 HPs, faster roll-out/supply compared to R290 HPs
2021-2022	-1,1%	-14,1%	+10,1%	+1,0%	Intro of new R290 HPs, start of the a new funding scheme in 2021 (BEG)
2022-2023	-0,5%	-0,3%	-3,1%	+8,6%	Simplified access of (multi-)split HPs (mainly R32) to German funding Supply issues for R290 HPs

Figure 5-30: Annual change of refrigerant usage between 2017 and 2023.

5.5.2 Life Cycle Assessment of Heat Pumps and Refrigerants

This work explores environmental assessment metrics beyond climate change, focusing on heat pumps and refrigerants in existing buildings in Germany. An extensive review of literature and databases provides the foundational data for evaluating these metrics simultaneously. Despite a scientific consensus on the basics of heat pumps and refrigerants, certain assumptions are necessary to yield meaningful results, indicating that further research is essential. A significant finding is that for low GWP refrigerants in heat pumps, the choice of refrigerant is less critical from an environmental perspective. Instead, factors such as resource availability (especially fluorine) and proper handling to prevent leakage are crucial. Currently, emissions from electricity generation are the primary environmental impact of heating with heat pumps. Transitioning to renewable electricity will shift some burdens but significantly reduce most environmental impacts, making the production processes of heat pumps and refrigerants more important for further reducing impacts. Future research should explore improvements in the supply chains of materials and refrigerants through dynamic LCA.

The electricity demand from heat pump operation represents the largest share of the total environmental impacts across most categories (orange, Figure 5-31). The only exception is ozone depletion, which is primarily due to leakage of fluorine-containing intermediates during refrigerant production. In all other categories, the impact of refrigerant production is negligible, with heat pump production being the second largest contributor to environmental impacts. Specifically, heat pump production significantly affects ecotoxicity, human toxicity, and resource consumption for all refrigerants except R717, as it does not involve copper.

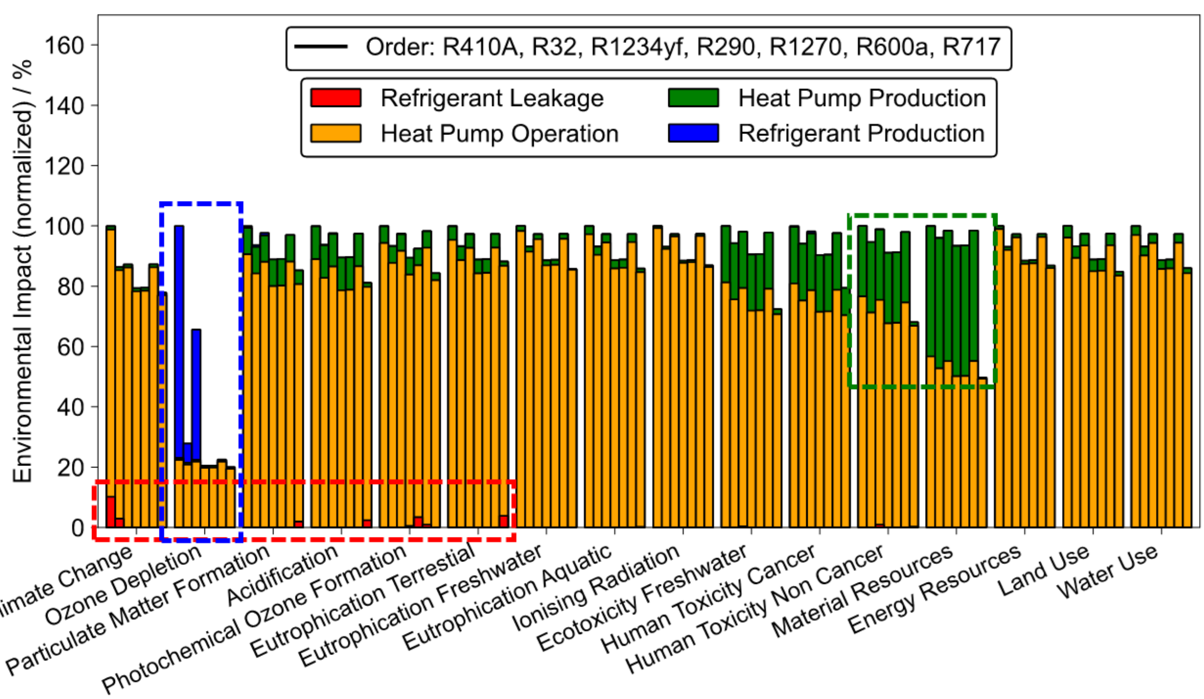


Figure 5-31: The environmental impact of the refrigerant on several categories.

Refrigerant leakage during operation (red) is the smallest contributor and varies by refrigerant and environmental category. High-GWP refrigerants R410A and R32 increase

GHG emissions, while R717 leakage has minor impacts on particulate matter formation, acidification, and terrestrial eutrophication. R717 consistently causes the lowest environmental impacts across all categories due to its high efficiency and lower electricity requirement, making it the most environmentally friendly refrigerant. The hydrocarbons R290 and R1270 also result in low environmental impacts due to their efficiency, which reduces electricity demand compared to HFOs and R600a. R32 is efficient but has a high GWP, leading to significant GHG emissions upon leakage. R600a and R1234yf have higher environmental impacts due to lower efficiencies. R410A has the highest environmental impacts in all categories, with significant GHG emissions and ozone depletion from production and leakage.

To summarize, switching to heat pumps can reduce environmental impacts in climate change, ozone depletion, photochemical ozone formation, and energy resource consumption across all five electricity mixes. However, impacts on eutrophication, freshwater and human toxicity, carcinogenicity, resource consumption, and water consumption increase. Even with renewable energy sources, wind power, and photovoltaics, environmental impacts cannot be reduced in all categories. Switching from a gas-condensing heating system to a heat pump always involves burden-shifting, where reducing impacts in one category increases them in another. For instance, switching to an air-to-water heat pump reduces GHG emissions but increases impacts in other categories. The acceptability of burden-shifting depends on the categories affected. Reducing GHG emissions is a high priority, making some burden-shifting acceptable.

The Planetary Boundary framework helps assess whether burden-shifting compromises overall sustainability. This framework outlines nine boundaries critical for Earth's ecosystem stability, including climate change, land use, and biogeochemical cycles of nitrogen and phosphorus. Five boundaries, such as climate change and eutrophication, have already been transgressed, so shifting burdens to these categories should be avoided. Achieving sustainable domestic heating involves environmental, social, and economic aspects, such as health and refrigerant cost, beyond just choosing refrigerants for heat pumps.

5.5.3 Reference

References to Section 5.5.1

The work was part as a project obligation for national projects like LC150 (FKZ 03EN4001A) and was yet nowhere else published.

References to Section 5.5.3

Vering, Christian (Corresponding author); Zibunas, Christian; Tessarek, Felix; Moschner, Nils; Breuer, Katharina Theresa; Höges, Christoph; Romberg, Hannah; von der Aßen, Niklas Vincenz; Müller, Dirk, Towards integral assessment of heat pumps and refrigerantsusing LCA: A case study for the German building stock, Heat Pump Conference 2023, Chicago.

	GE	SDS
Climate Change	-30 %	-79 %
Ozone Depletion		
Particulate Matter Formation		
Acidification		
Photochemical Ozone Formation		
Eutrophication Terrestrial		
Eutrophication Freshwater		
Eutrophication Aquatic		
Ionizing Radiation		
Ecotoxicity Freshwater		
Human Toxicity Cancer		
Human Toxicity Non Cancer		
Material Resources		
Energy Resources		
Land Use		
Water Use		

Figure 5-32: Comparison of an air-to-water heat pump with a gas condensing boiler to estimate the potential of burden-shifting in several environmental impact categories for two electricity mixes (GE and SDS).

5.6 Overall conclusions

In several case studies, the report shows the diverse spectrum of heat pump research working in the field of applying low-GWP refrigerants. It reports on the diverse spectrum of institutions involved in this process for evaluation, development of refrigerants, refrigerant-oil mixtures, and components, as well as systems for heat pumps mainly operated as vapor compression systems. Here, not only efficiency but also safety topics are and were applied to cope with the increasing flammability of low-GWP refrigerants. It is worth mentioning that here, mainly, the knowledge was improved for charge reduction measures for optimized and safer cycle design as well as for the safety analysis after a release in case of a leakage. Next to vapor compression heat pumps, the research investigated tumble dryers, thermal management systems for electric vehicles (buses), as well as hybrid and absorption heat pumps.

By a thorough analysis of product data as well as funding applications the supply side and the demand side were studied. Based on this the transition process to low-GWP refrigerants for residential heat pumps was investigated. It was shown by the analysis of the supply side (product databases) that already available products of R290 heat pumps results usually in the highest achievable performance. The first significant run for R290 residential heat pumps was in 2012 but no data for their market share were available. A continuous dataset has been available for the time since 2016. Here, the introduction of new R290 heat pumps in 2018 led to a recognizable share starting from 2019. For heat pumps in residential houses, this resulted in a 20% share for all heat pump types in 2023. The first increase in its share for R32 systems started about one year later in 2020. Until now, R32 as refrigerant gained even a larger share but reflects systems that are mainly imported to the German heat pump market. The share of R410A systems is still at about 40% in

2023. However, the significant drop in R410A share, as well as the added production capacity due to the forecasts for higher volumes of sold units since 2022, makes a complete transition probable to low-GWP refrigerants in accordance with the F-gas regulation.

Continuous monitoring of heat pump systems since 2006 has been performed, including the latest projects which concluded in 2019. These studies have primarily focused on assessing the efficiency of heat pumps, their capability to operate in a "smart-mode" which interacts efficiently with renewable electrical energy sources, and the CO_2 avoidance potentials. The latter depends highly on the CO_2 equivalent emissions by the electrical energy production for which the share changed during the duration of Annex 54 from 29% in 2016 to 53% in 2023[1].

[1] www.energy-charts.info

5.7 Acknowledgements

Fraunhofer ISE would like to pay special regards to all contributing institutions and especially the funding of the BMWK to facilitate our participation at the IEA Annex 54 work by the projects safeSense (FKZ 03EN2030A), LC150 (FKZ 03EN4001A) as well as the provision of funding application data from the BAFA to facilitate the market analysis in all the years.

RWTH Aachen would like to pay special regards to all contributing institutions and especially the funding of the EU (EFRE) and BMWK to facilitate our participation at the IEA Annex 54 work by the projects Urban Energy Lab 4.0 (EFRE-0500029) and LOGIN (FKZ: 03EN4011).

www.heatpumpingtechnologies.org

Heat Pump Centre
c/o RISE - Research Institutes of Sweden
PO Box 857
SE-501 15 BORÅS
Sweden
Tel: +46 10 516 53 42
E-mail: hpc@heatpumpcentre.org

www.heatpumpingtechnologies.org

Report no. HPT-AN54-6