



Welcome to the 14<sup>th</sup> IEA  
Heat Pump Conference, 2023

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The Future of Refrigerants for  
Heat Pump Applications

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Who Wants to Be a Millionfold  
Deployed Refrigerant?

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# Heat Pumping Technologies MAGAZINE

A HEAT PUMP CENTRE PRODUCT

The next step in mitigating climate change:  
**Refrigerants**

RELEASE OF IEA'S ENERGY EFFICIENCY 2021 REPORT

"TOTAL ANNUAL INVESTMENT IN GLOBAL ENERGY  
EFFICIENCY NEEDS TO TRIPLE BY 2030 – TO KEEP  
GLOBAL CLIMATE PLEDGES WITHIN REACH"

VOL.40 NO 1/2022

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# Heat Pumping Technologies MAGAZINE

VOL.40 NO.1/2022

## In this issue

As the adverse effects of climate change continue to manifest in extreme, deadly, and costly weather events, the increasing need for developing alternative countermeasures in the fight against global warming is becoming second to none. Refrigerants are the key resource in (almost) all refrigeration, air conditioning and heat pump systems; however, with a few exceptions from natural refrigerants, if released into the atmosphere, they are a strong catalyst contributing to global warming. Yet, if their chemical composition is being engineered correctly, they can be a clear vector to reducing the systems' direct CO<sub>2</sub> equivalent emissions; the challenges and prospects of Low GWP refrigerants are discussed in the foreword of this issue.

The search for the future ideal refrigerant is not new but has been ongoing for over a century, even though the reason for the search has changed. Under the title of "We Stand Again at a Historic Crossroads", the column section explores the journey to natural refrigerants like hydrocarbons, ammonia and carbon dioxide.

In this issue, you can read a summary of the European Commission's (EC) newly revised Energy Performance of Buildings Directive (EPBD) proposal, an excerpt from the IEA's Renewable 2021 and Energy Efficiency 2021 reports, and a summary of the IEA's 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas in the HPT news in focus section.

Under the theme of "Refrigerants", the topical articles of this issue are all addressing (i) the criteria for the selection of working fluids for vapour compression refrigeration and heat pump systems, and (ii) the role of refrigerants in determining whether systems are efficient, safe, environmentally friendly, economical, and effective in mitigating the Global Warming Impact.

Enjoy your reading!

Metkel Yebiyi, Editor

**Heat Pump Centre**

The central communication activity of Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

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## Low GWP refrigerants – system solutions and components

While the adverse effects of climate change continue to manifest in extreme, deadly, and costly weather events, we are competing with this climate emergency in a race for the urgent development of alternative countermeasures. Refrigerants used in all refrigeration, air conditioning, and heat pump systems are like blood to human health. While unique characteristics of natural refrigerants such as flammability, toxicity, and high operating pressures short-sighted us to use synthetic refrigerants as a solution in the early stage of refrigeration system development history, unforeseen long-term environmental adverse effects of the synthetic refrigerants eventually have forced their phase-out or phase-down.



As the human body needs a good balance of LDL (low-density lipoprotein, called bad cholesterol) and HDL (high-density lipoprotein called good cholesterol), and low enough total cholesterol for a healthy heart, carbon emissions from refrigeration, air conditioning, and heat pump systems also need to have a good balance of reducing the GWP of refrigerants (like lowering the LDL) and increasing the system efficiency (like increasing the HDL) to eventually lower the total emissions (like lowering total cholesterol). As the cardiologist recommends taking prescribed drugs and lifestyle changes for people with high LDL or total cholesterol levels exceeding the threshold values, we need to replace the high GWP refrigerants with lower GWP ones and improve the system efficiency. Like most medicine have a net positive effect of curing their targeted illness but are accompanied by unavoidable side effects, alternative lower GWP refrigerants have several challenges of flammability and different thermophysical properties and operating characteristics from the existing systems needing new safety measures and optimization of components and systems. Under this climate emergency, we need to make all refrigeration, air conditioning, and heat pump systems take a good medicine of using lower GWP refrigerants as soon as possible and lifestyle changes like adopting natural refrigerants to save our patient, the Earth in time.

As part of the ongoing global research alliance in refrigerants, the [Annual Report 2021](#) for Annex 54 – Heat Pump Systems with Low-GWP Refrigerants is now available. This report provides a comprehensive, most up-to-date review of current research and the development of systems and their optimizations using low-GWP refrigerants for heat pump applications. It also includes a state-of-the-art review of life cycle evaluations of such systems using low-GWP refrigerants. It summarizes the collective efforts by researchers, engineers, and regulation committees across the industry.

**Yunho Hwang**  
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## We Stand Again at a Historic Crossroads

The vast majority is taking advantage of refrigerants in their daily life, most often without thinking or even knowing about it. While the readers of HPT Magazine know that refrigerants are the magic key to harvesting energy in the form of heat at one temperature and making it valuable simply by compressing the refrigerant.

With today's great need to de-carbonize our societies to have a chance to keep the global warming below 1,5 °C, it's no surprise that heat pumps are likely to play an even more important role in the future. This is reflected in projections such as the [International Energy Agency's Net-Zero by 2050 Roadmap](#), as well as political support embodied in regulations like the [European Commission's Energy Performance of Buildings Directive](#). A similar increase can be foreseen for air conditioning units, as more and more people will be able to afford them, and that heatwaves will become even more common in the future than what they already are with today's global temperature rise of 1,2 °C.

So, we will use more refrigerants in the future. Does this also imply that more refrigerant will leak into the atmosphere? Yes, I believe so. I don't know any of our nearly 1000 member companies working with service of refrigeration installations and heat pumps that do not have a couple of refrigerant cylinders in the back of their vans to top up leaking systems, and that's for a reason. To claim that no leaks will occur would require that the entire chain of events involving refrigerants, i.e. production, transportation, filling, decommissioning, or recycling, must take place without any leaks.

But one might think, we are phasing out the ozone layer damaging CFC and HCFC refrigerants thanks to the Montreal protocol, and through the Kigali amendment, we are phasing down the use of HFC, potent greenhouse gases. Not phasing out those would have led to global warming of up to 0.4 °C in 2100, solely [1]. Should not this be enough? Is it really a problem that the most recent generation of fluorinated refrigerants, unsaturated HFCs, also called HFOs, ends up in the atmosphere?

What we know is that once released into the atmosphere, the molecule will decompose into smaller parts due to the double bond in the refrigerant's carbon chain. Therefore, the global warming potential is much lower than for the more stable HFC refrigerants, which do not have this double bond. The bond between the carbon and fluorine atoms in the refrigerant, on the other hand, is strong, making this part of the decomposed refrigerant persistent. Trifluoroacetic acid (TFA) is one of the substances produced by the decomposition of some HFCs such as R134a (20% yield) and HFOs such as R1234yf (100% yield). TFA is a strong acid washed out of the atmosphere by precipitation as a form of "acid rain" to the earth. Arctic ice core samples have shown a significant increase in TFA [2] from that point in time when the Montreal Protocol initiated the change in refrigerants used. Another study, this time from Germany and on the amount of TFA in precipitation over two years, shows a yearly fluctuation, with a mean peak value of TFA of slightly more than 1 µg/L for both years [3]. Taking into account that TFA levels should not be higher than 10 µg/L to keep our drinking water safe for us, according to a study by the German Environment Agency [4], this indicates that the possibility to increase the use of HFO refrigerants is limited.

The easiest way to avoid any potential environmental issues caused by refrigerant leaks is to use natural refrigerants. Of course, there will be challenges with those as well: How can operations safety be ensured, and high efficiency be maintained? But those challenges should not be overestimated – we have been handling flammable substances for decades, even with larger quantities in many applications, like gas for stoves or petrol in cars. High efficiency can with the correct design and the good thermodynamic properties of the natural refrigerants be ensured.

The choice of future refrigerants is up to the few of us who work with this magic.

VIKTOR ÖLÉN

Swedish refrigeration and  
heat pump association



# The European Commission (EC) published a proposal for a new revision of the Energy Performance of Buildings Directive (EPBD) on December 15 – paves the way for heat pumps to become the norm for heating of buildings in Europe



## [“European Green Deal: Commission proposes to boost renovation and decarbonization of buildings”](#)

The European Commission (EC) published a new revision of the Energy Performance of Buildings Directive (EPBD) on December 15, as part of the "Fit for 55" Commission Work Programme package for 2021, which aims to make the EU's climate, energy, land use, transportation, and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. The main objective of this revision is to reduce greenhouse gas (GHG) emissions and final energy consumption in buildings by 2030, as well as to establish a long-term strategy for buildings that would lead to EU-wide climate neutrality by 2050. In order to achieve this reduction, the initiative is focused on several specific objectives, such as increasing the rate and depth of building renovations, improving information on energy performance and building sustainability, and ensuring that all buildings satisfy the 2050 climate neutrality requirements. The levers for achieving these goals include increased financial assistance, modernization, and system integration. Hence, this proposal paves the way for heat pumps to be the most common heating system for buildings in Europe, in line with [IEA's Net-Zero by 2050 Roadmap](#).

The [proposal](#) is particularly important, according to the EC, because buildings account for 40% of the energy consumed and 36% of energy-related direct and indirect greenhouse gas emissions. Heating, cooling, and domestic hot water account for 80% of household energy use in the EU, making Europe more resilient calls for renovation of EU buildings, making them more energy-efficient and less dependent on fossil fuels. Renovation is key for reducing the energy consumption of buildings, bringing down emissions, and reducing energy bills. In addition, renovations create jobs and economic growth in the area.

According to the Commission, all new buildings must be zero-emission by 2030, and according to the latest [European Heat Pump Outlook 2021](#), heat pumps are fast becoming the standard solution for new buildings, and in combination with smart renovation, heat pumps are a feasible option also in the existing buildings. To harness the potential of faster action in the public sector, all new public buildings must be zero-emission by 2027. This means that buildings must use little energy, be powered by renewables as far as possible, emit no on-site carbon

emissions from fossil fuels and must indicate their global warming potential based on their whole-life cycle emissions on their Energy Performance Certificate. Based on the [Commission's 2020 system integration strategy](#), the rapid growth and cost competitiveness of renewable electricity production can service a growing share of electricity demand, for instance, using heat pumps for space heating or low-temperature industrial processes, electric vehicles for transport, or electric furnaces in certain industries.

When it comes to renovations, new EU-level minimum energy performance standards are proposed, requiring the **worst-performing 15% of the building stock of each Member State to be upgraded** from the Energy Performance Certificate's Grade G to at least Grade F by 2027 for non-residential buildings and 2030 for residential buildings.

HPT TCP has recently approved a new international collaboration project, an annex, titled **Retrofit Heat Pump Systems in Larger Non-domestic Buildings**, to be started in 2022. The outcomes and learnings from this project will support stakeholders in charge of renovating their buildings to reach minimum energy performance standards.

Several stakeholders have welcomed the ambitious proposal on the decarbonization of heating and cooling systems in the EU's buildings, which drastically improves the case for heat pumps. The Commission's clear statement on phasing out fossil fuels in heating and cooling by 2040 is, according to the [European Heat Pump Association \(EHPA\)](#), the shift needed to swiftly implement decarbonization of heating. By ending financial incentives for fossil fuel boilers as of 2027, the EC implements the polluter pays principle and enables citizens to switch to heat pumps. However, according to them, the Commission should have been more ambitious on buildings in 2050 and aimed for more positive energy buildings (enabled by heat pumps). Moreover, other [voices](#) claimed that Fit for 55 Part II, which includes the revised EPBD, does not reflect a climate emergency and sends conflicting messages to the international community about the EU's commitment to phase out fossil fuels.

[Read the press release of the EC on the proposal release of the EPBD revision.](#)

# Are renewable heating options cost-competitive with fossil fuels in the residential sector?

## Release of IEA's Renewable 2021 report

The **Renewables 2021** report is the IEA's primary analysis on the sector, based on current policies and market developments. [The report](#), released on the 1st of December 2021, shows that the world is set to add more renewable power capacity in 2021 than ever before. The record-breaking additions of 290 GW of solar, wind, and other renewables are yet another sign that a New Global Energy Economy is emerging, according to their analysis see Figure 1.

New analysis from IEA expects renewables to account for almost 95% of the growth in global power capacity through 2026, with solar PV alone providing more than half. This is driven by stronger support from policies and more ambitious pledges made going into just before the COP26 meeting.

Moreover, the report states that **"the rising share of renewables in the power sector and heat pump deployment are the main drivers of renewable heat growth in buildings"**.

This year's edition also includes a chapter on renewable energy trends to watch, including for example: [Are renewable heating options cost-competitive with fossil fuels in the residential sector?](#)

This article summarizes the parameters affecting the cost-competitiveness of heating technologies for different renewable heating technologies such as heat pumps, bioenergy and solar heating. It is clearly seen that these parameters differ from region to region primarily due to market maturity, energy prices and the policy landscape. Along with the article, IEA also launched a **Residential heat economics calculator** allowing users to explore and compare the economics of different residential heating systems, including varying different parameters. The concluding remark in this article is that scaling up the use of renewable heating in buildings requires policy-makers to address economic as well as non-economic challenges through comprehensive and multidimensional policy approaches. These can, according to the article, potentially include a combination of awareness-raising campaigns, regulatory measures and economic incentives, which – most importantly – should place social justice at the heart of the transition.



Read the press release [here](#).

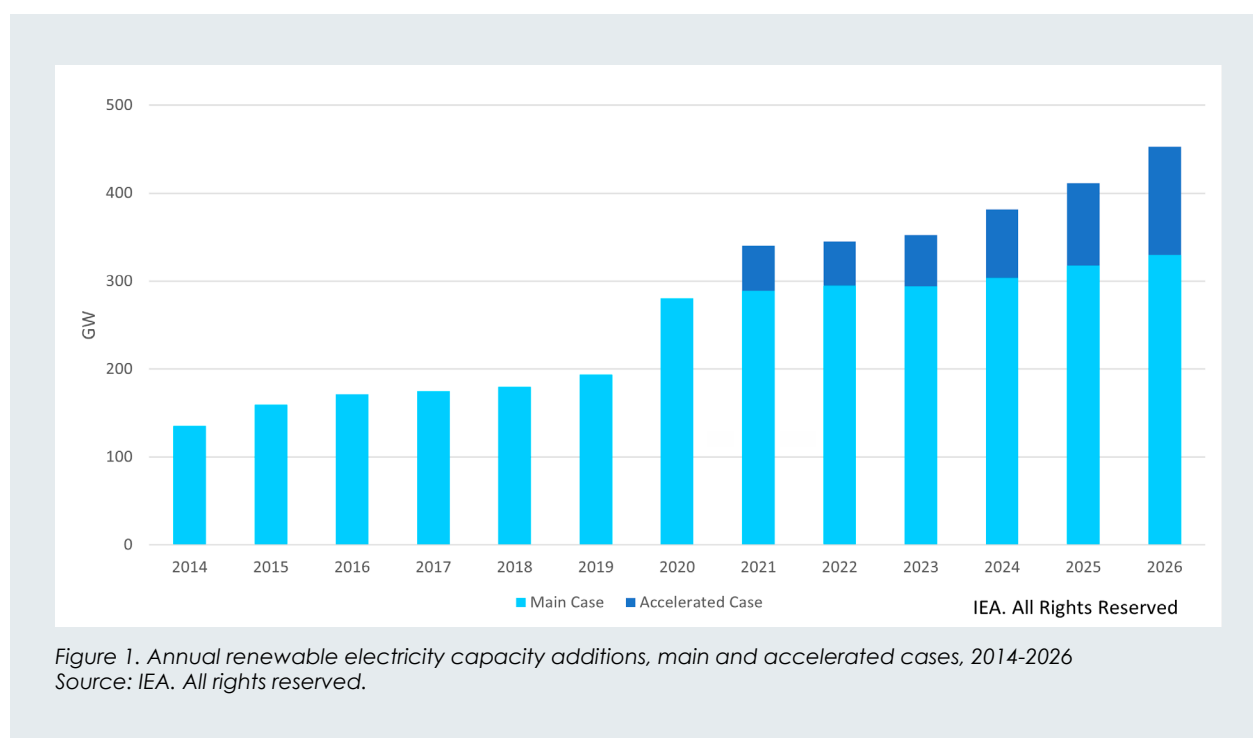


Figure 1. Annual renewable electricity capacity additions, main and accelerated cases, 2014-2026  
Source: IEA. All rights reserved.

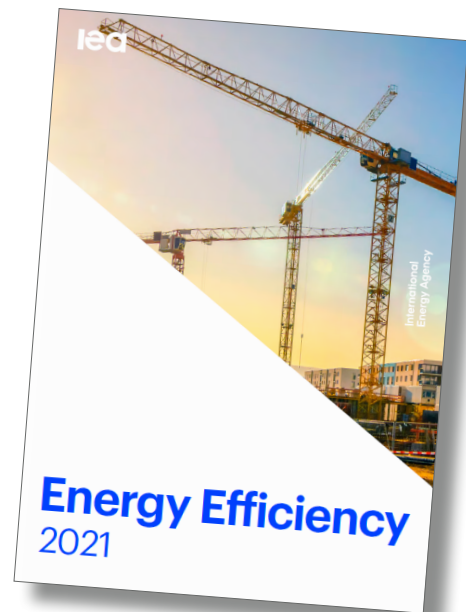
# Total Annual Investment in Global Energy Efficiency Needs to Triple By 2030 – To Keep Global Climate Pledges Within Reach

Release of IEA's Energy Efficiency 2021 report

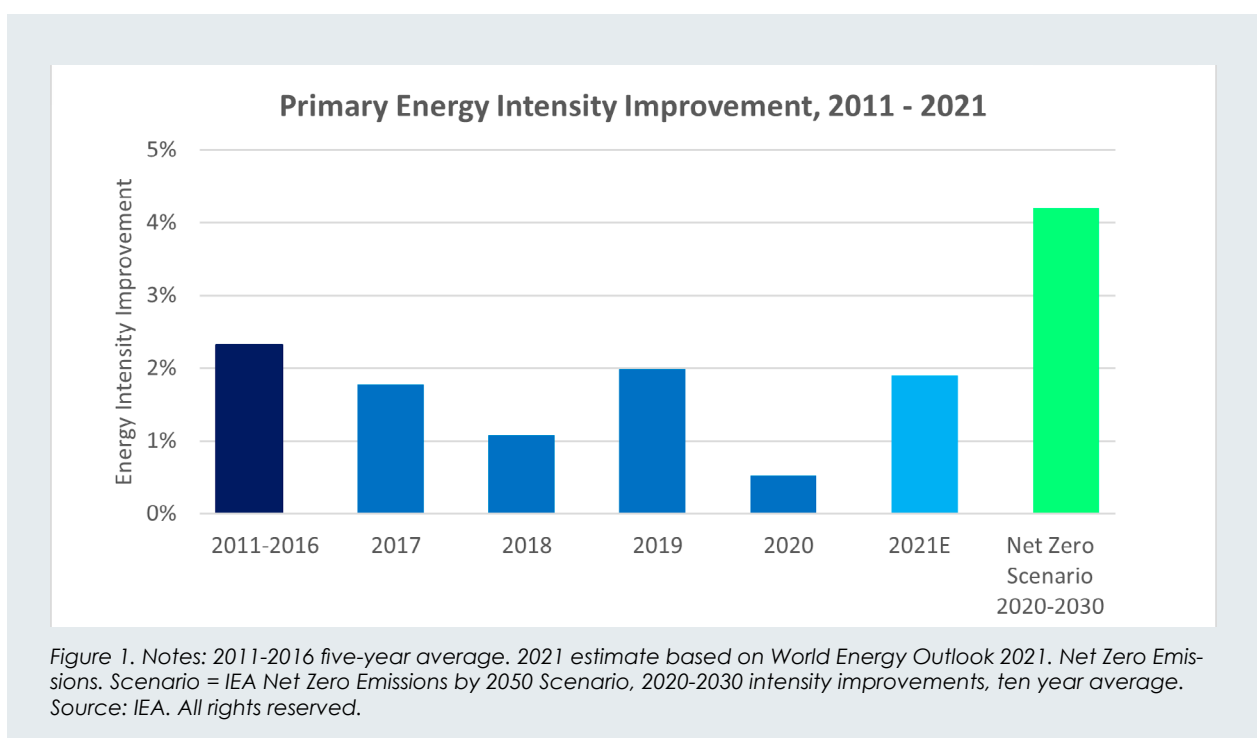
Global progress on energy efficiency has recovered this year to its pre-pandemic pace, but that was already well short of what would be needed to help put the world on track to reach net-zero emissions by mid-century, according to [Energy Efficiency 2021](#), the IEA's annual update on global developments in energy efficiency. Total annual investment in energy efficiency worldwide needs to triple by 2030 to be consistent with a path towards reaching net zero emissions by 2050, as set out in the IEA's [Roadmap to Net Zero by 2050](#).

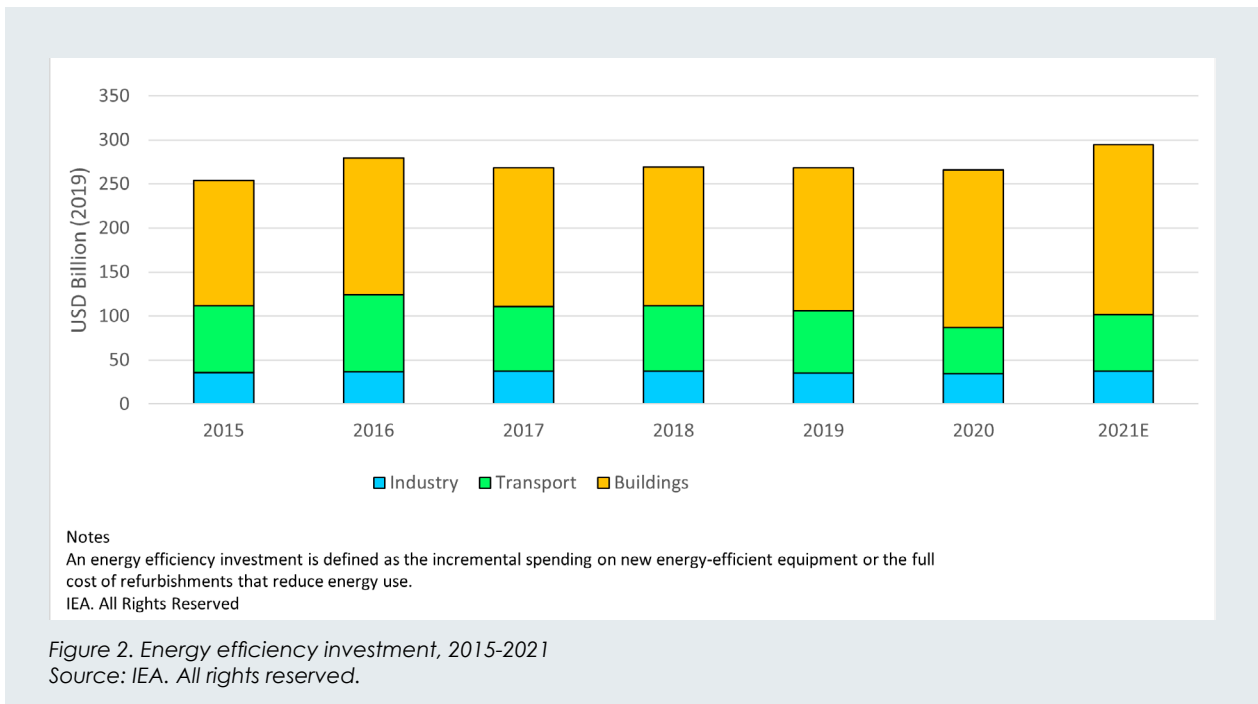
The report underlines that when the Covid-19 pandemic shifted the centre of economic activity away from services and towards industry, the rate of improvement in global energy intensity – a key indicator of how efficiently the world's economic activity uses energy is expected to recover in 2021 to 1.9%. The report highlights that this is in line with the average annual rate of improvement over the past 10 years but well below the 4% needed between 2020 and 2030 in the IEA's pathway to net zero emissions by 2050, see Figure 1.

The IEA report shows that recent investment growth has been concentrated mainly in Europe, suggesting policies



are needed in other regions to achieve global climate goals. Moreover, the report states that Government policies had





been expected to help energy efficiency investment rise by 10% in 2021 to almost USD 300 billion see Figure 2. However, to be consistent with levels foreseen in the [IEA Net Zero Emissions by 2050 Scenario](#), the overall annual investment would need to triple by 2030.

In addition, according to the IEA Net Zero Emissions by 2050 Scenario, an early policy focus on energy efficiency would triple the number of jobs created by 2030 through increased spending on building retrofits, more efficient appliances and other measures. This includes many jobs in construction, as well as installation of heating, cooling and hot water systems. HPT TCP by IEA has a new international collaboration project, [Annex 60](#), titled Retrofit Heat Pump Systems in Larger Non-domestic Buildings. The outcomes and learnings from this project will support building owners, design engineers, or policy makers to better understand system integration and the several possible ways of retrofitting heat pumps.

The [Energy Efficiency 2021](#) report shows that the electrification of transport, space and water heating and many industrial applications results in increased efficiency and lower emissions but contributes to electricity generation rising by 40% by 2030 in the Net Zero Emissions by 2050 Scenario. Electric equipment is much more efficient than their equivalents powered directly by fossil fuels, with electric heat pumps, for example, being three to four times more efficient than burning fossil fuels for heat, see previous [news release](#) by the Heat Pump Centre on this topic. The Global goals to reduce GHG emissions necessitate a significant reduction in fossil-fuel-based heat supply for industrial activities. To address and devise a sustainable solutions for this, the HPT TCP by IEA has two ongoing international collaboration projects, [High-Temperature Heat Pumps – Annex 58](#) and [HP for Drying – Annex 59](#).

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social media





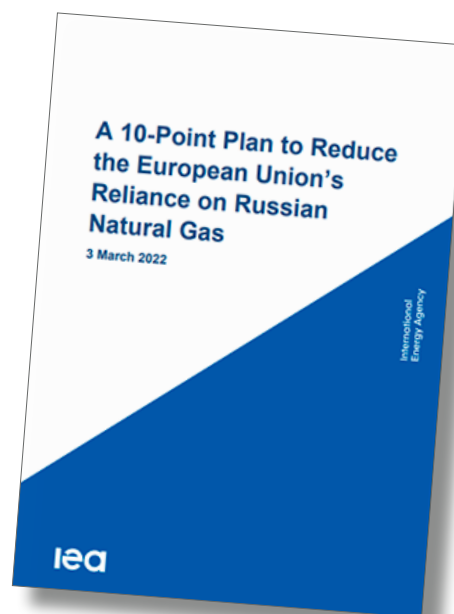

# IEA has launched 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas – Heat pumps are part of the solution

The International Energy Agency (IEA) released a [10-point plan](#) on March 3 to reduce the European Union's reliance on Russian natural gas. They claim that actions taken this year may reduce Russian gas imports by more than a third, with additional interim options to reduce them by more than half while still cutting emissions.

Europe's reliance on Russian natural gas has once again become a hot topic due to Russia's invasion of Ukraine on February 24. The report shows that the European Union imported 155 billion cubic meters of natural gas from Russia in 2021, accounting for over 45% of EU gas imports and nearly 40% of its total gas consumption, see Figure 1. Progress toward Europe's net-zero goals will reduce gas use and imports over time, but the current crisis highlights specific considerations regarding Russian imports and what policymakers and consumers can do to reduce them. The IEA report offers a set of immediate changes that might be adopted to minimize dependency on Russian gas while also improving the EU gas network's near-term resilience and easing the burden on vulnerable users.

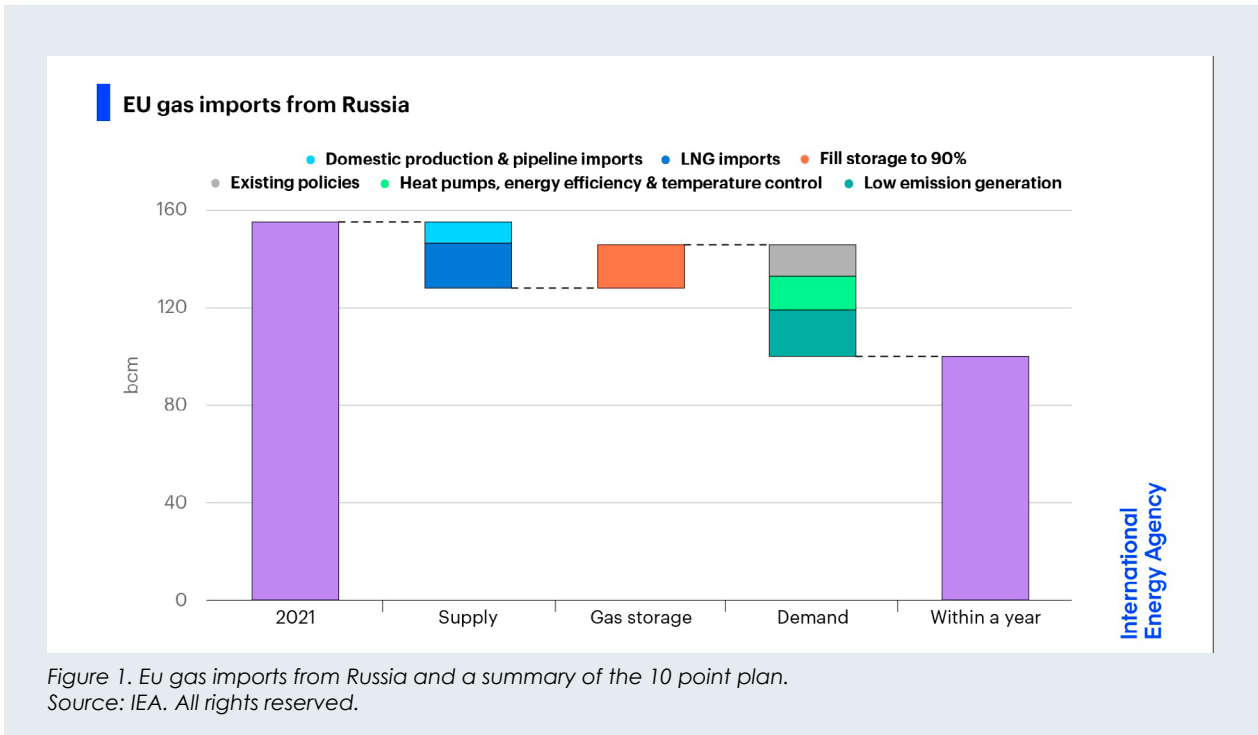
Not signing any new gas supply contracts with Russia; drawing on other energy sources and accelerating efforts to provide consumers, businesses, and industries with the means to use clean and efficient alternatives to natural gas; speeding up the replacement of [gas boilers with heat pumps](#) (which the Strategic Work Plan of [HPT TCP](#) also aims at), accelerate energy efficiency improvements in buildings and industry, accelerating the deployment of solar and wind; making the most of existing low-emission energy sources, such as nuclear and renewables; are among the key actions recommended, in the [IEA's 10-Point Plan](#). The proposed measures are also entirely with the [EU's European Green Deal and its Fit for 55 package](#), paving the way for future emissions reductions.

Many of the recommendations in the plan are major elements of the [IEA's Roadmap to Net Zero by 2050](#), including increasing energy efficiency measures, speeding renewable deployment, and extending low-emission sources of power system flexibility. The IEA predicts that if these initiatives are taken combined, the European Union's Russian gas imports could be reduced by more than 50 billion cubic meters, or more than one-third, within a year.



A bullet-point summary of the 10-point plan is given below. [Read the press release.](#)

1. Do not sign any new gas supply contracts with Russia. **[Impact:** Enables greater diversification of supply this year and beyond]
2. Replace Russian supplies with gas from alternative sources **[Impact:** Increases non-Russian gas supply by around 30 billion cubic metres within a year]
3. Introduce minimum gas storage obligations **[Impact:** Enhances resilience of the gas system by next winter]
4. Accelerate the deployment of new wind and solar projects **[Impact:** Reduces gas use by 6 billion cubic metres within a year]
5. Maximise power generation from bioenergy and nuclear **[Impact:** Reduces gas use by 13 billion cubic metres within a year]
6. Enact short-term tax measures on windfall profits to shelter vulnerable electricity consumers from high prices **[Impact:** Cuts energy bills even when gas prices remain high]
7. **Speed up the replacement of gas boilers with heat pumps** **[Impact:** Reduces gas use by an additional 2 billion cubic metres within a year]



8. Accelerate energy efficiency improvements in buildings and industry [**Impact:** Reduces gas use by close to 2 billion cubic metres within a year]
9. Encourage a temporary thermostat reduction of 1 °C by consumers [**Impact:** Reduces gas use by some 10 billion cubic metres within a year]
10. Step up efforts to diversify and decarbonise sources of power system flexibility [**Impact:** Loosens the strong links between gas supply and Europe's electricity security]

Concerning bullet point **7. Speed up the replacement of gas boilers with heat pumps**; the report states that

- » Heat pumps offer a very efficient and cost-effective way to heat homes, replacing boilers that use gas or other fossil fuels. Speeding up anticipated deployment by doubling current EU installation rates of heat pumps would save an additional 2 bcm of gas use within the first year, requiring a total additional investment of EUR 15 billion.
- » Alongside existing policy frameworks, targeted support for investment can drive the scaling up of

heat pump installations. Ideally, this is best combined with upgrades of the homes themselves to maximise energy efficiency gains and reduce overall costs.

- » Replacing gas boilers or furnaces with heat pumps is also an attractive option for industry, although deployment may take longer to scale up.
- » Depending on the situation, a shift from gas to electricity for heating buildings could have the corresponding effect of pushing up gas demand for power generation. However, any increase would be much lower than the overall amount of gas saved. Such a shift would also transfer seasonal swings in demand from the gas market to the power market.

The HPT TCP is continuously providing IEA with facts and data, which contributes to this type of analyses made by IEA.

# Welcome to the 14<sup>th</sup> IEA Heat Pump Conference, 2023



Every three years, the Technology Collaboration Programme on Heat Pumping Technologies by IEA (HPT TCP by IEA) convenes the IEA Heat Pump Conference. The United States is proud to announce that it will be hosting the upcoming 14<sup>th</sup> IEA Heat Pump Conference, which will be held in **Chicago on 15-18 May 2023**. The theme for the Conference is **“Heat Pumps – Resilient and Efficient”**.

## Conference goals

Clean, efficient, and reliable energy systems are essential to meeting basic needs for comfortable, secure, and environmentally friendly building environments, food processing, transport, storage; and industrial processes. Many analysts estimate that it will not be possible to achieve long-term climate, security, and energy goals without increasing the use of renewable heating and cooling technologies in conjunction with large-scale refurbishment and renovation of the world’s existing buildings and industrial infrastructure. Heat pumps, driven with renewable power sources, are the key technical solution for meeting these challenges.

The upcoming 14<sup>th</sup> IEA Heat Pump Conference will serve as a forum to discuss the latest heat pumping technologies and applications, and exchange valuable knowledge in research, market, policy, and standards information on related technologies. Exhibitions will be held during the Conference to share heat pumping products and technologies.

## Conference program highlights

The National Organizing Committee (NOC), chaired by Brian Fricke, looks forward to providing conference attendees with an exceptional conference experience, in keeping with the tradition of excellence established by all 13 of the preceding conferences.

Conference program highlights include the following:

- » High level invited speakers for the opening plenary sessions
- » High level invited keynote speakers leading each major conference oral technical session
- » Poster presentation sessions associated with each oral technical session
- » Exhibition of equipment and information kiosks
- » Technical visits
- » Social and sight-seeing program

The Conference will start on Monday (15 May 2023) with a series of Workshops on international collaborative projects (Annexes) within the HPT TCP by IEA and other related topics. After the main plenary opening sessions on Tuesday morning (16 May 2023), the remaining two and one-half days will consist of oral and poster technical sessions organized in parallel tracks, featuring a number of heat pump related topics including, but not limited to, the following:

- » Residential and commercial building comfort conditioning, focusing on topics such as: space heating, air-conditioning, net-zero buildings, renovation, hybrids, domestic hot water, and multifamily buildings.
- » Non-residential applications, focusing on industrial heat pumps, waste heat, district heating, commercial refrigeration, and transport air conditioning and refrigeration.
- » Innovation and Research and Development (R&D), focusing on aspects such as ground sources, advanced storage systems, working fluids, sorption technologies, advanced vapor compression, non-vapor compression technologies, smart grids/energy, cold and hot climate applications, advanced air

conditioning technologies, gas-driven heat pumps and combinations with other renewable technologies.

- » Policy topics and market status, trends, strategies, and future opportunities.

**Who should attend?**

The wide variety of heat pump related discussions that will take place during the Conference is intended to attract a diverse group of attendees, including:

- » Policy makers, government officials, energy efficiency program leaders
- » Executives and representatives from industry, utilities, and the public sector
- » Manufacturers, distributors, and technology supporters
- » Designers and developers of heat pump systems and components
- » Researchers from industry, utilities, academia, and private and public R&D institutes

**Conference information**

Those wishing to attend the Conference should visit the conference website: [www.hpc2023.org](http://www.hpc2023.org). Detailed information, including registration and hotel accommodation forms, will be available together with a second announcement in autumn 2022.

**Conference venue**

The Renaissance Chicago Downtown Hotel is excited to welcome the 14<sup>th</sup> IEA Heat Pump Conference attendees, “Resilient and Efficient.” Located in the prime area of the Theater District, the venue provides attendees with easy access to Chicago’s vibrant cultural infrastructure, including a wide variety of traditional pubs, eclectic bars, and clubs. Chicago is also home to a wide variety of restaurants satisfying most any culinary desire. The Chicago O’Hare International Airport (ORD) and Midway Interna-



tional Airport (MDW) are international and domestic arrival hubs offering light rail service to downtown Chicago, and ground transportation such as taxis and ride-share services are readily available.

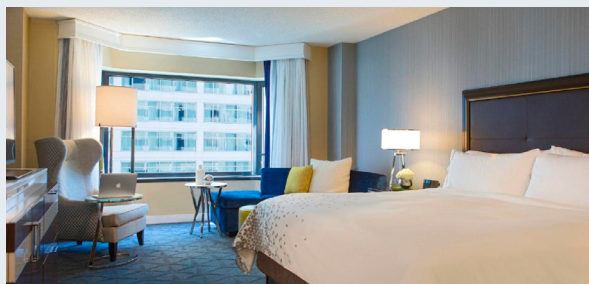
Additional updates and details will be provided on the website of the conference [www.hpc2023.org](http://www.hpc2023.org) and via [www.heatpumpingtechnologies.org](http://www.heatpumpingtechnologies.org).

**Call for papers**

Abstracts (250 words maximum) covering the conference theme may be submitted on the conference website until 15 May 2022. The abstracts will be screened, and authors will be advised of acceptance by 15 June 2022.

**Important conference dates:**

- » Abstract submission opened 15 November 2021
- » **Abstract submissions due 15 May 2022**
- » Authors advised of acceptance 15 June 2022
- » Full paper submissions due 15 November 2022
- » Final paper submissions due 15 February 2023



Chicago Venue

## Ongoing Annexes in HPT TCP

The projects within the HPT TCP are known as Annexes. Participation in an Annex is an efficient way of increasing national knowledge, both regarding the specific project objective, but also by international information exchange. Annexes operate for a limited period of time, and the objectives may vary from research to implementation of new technology.

HEAT PUMPS IN MULTI-FAMILY BUILDINGS FOR SPACE HEATING AND DHW	50	AT, CH, <b>DE</b> , DK, FR, IT, NL
LONG-TERM MEASUREMENTS OF GSHP SYSTEMS PERFORMANCE IN COMMERCIAL, INSTITUTIONAL AND MULTI-FAMILY BUILDINGS	52	DE, FI, NL, NO, <b>SE</b> , UK, US
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\*) Participates from ECES TCP



NEW



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The Technology Collaboration Programme on Heat Pumping Technologies participating countries are:

Austria (AT), Belgium (BE), Canada (CA), China (CN), Denmark (DK), Finland (FI), France (FR), Germany (DE), Italy (IT), Japan (JP), the Netherlands (NL), Norway (NO), South Korea (KR), Sweden (SE), Switzerland (CH), the United Kingdom (UK), and the United States (US). Turkey (TR\*), participates in joint Annex through Energy Storage TCP).

**Bold, red text** indicates Operating Agent (Project Leader).

ANNEX  
52LONG TERM PERFORMANCE  
MEASUREMENT OF GSHP  
SYSTEMS SERVING COMMERCIAL,  
INSTITUTIONAL AND  
MULTI-FAMILY BUILDINGS**Introduction**

Carefully instrumented and analyzed long-term performance measurements from large Ground Source Heat Pumps (GSHP) systems are highly valuable tools for researchers, practitioners and building owners. Analyses of good quality long-term performance measurements of GSHP systems are sparse in the literature, and there is no consensus on key figures for performance evaluation and comparison. Within Annex 52, a bibliography on long-term measurement of GSHP systems has been compiled, and the participants are measuring performance of more than 55 GSHP systems. Based on this experience, the annex is revising the current methodology to better characterize the performance of larger GSHP systems. These systems have a wide range of features and can be considerably more complex than single-family residential GSHP systems. The case studies will provide a set of benchmarks for comparisons of such GSHP systems around the world, using an extended system boundary schema for calculation of system performance factors. This schema is a further development of the [SEPEMO](#) system boundary schema developed for non-complex residential heat pump systems.

The outcomes from this annex will help building owners, designers and technicians evaluate, compare and optimize GSHP systems. It will also provide useful guidance to manufacturers of instrumentation and GSHP system components, and developers of tools for monitoring, controlling and fault detection/ diagnosis. This will lead to energy and cost savings.

**Objectives**

- » Survey and create a library of quality long-term measurements of GSHP system performance for commercial, institutional and multi-family buildings. All types of ground sources and ground heat exchangers are included in the scope.
- » Refine and extend current methodology to better characterize GSHP system performance serving commercial, institutional and multi-family buildings with the full range of features shown on the market, and to provide a set of benchmarks for comparisons of such GSHP systems around the world.
- » The guidelines provided by the [SEPEMO](#)

project will be refined and extended to cover as many GSHP system features as possible and will be formalized in a guidelines document.

**Key data**

- » Project duration: Jan 2018 – Dec 2021
- » Operating Agent: Signhild Gehlin, Swedish Geoenergy Center, [signhild@geoenergicentrum.se](mailto:signhild@geoenergicentrum.se)
- » Participating countries: Finland, Germany, Netherlands, Norway, Sweden, UK, USA
- » Website: <http://heatpumpingtechnologies.org/annex52/>

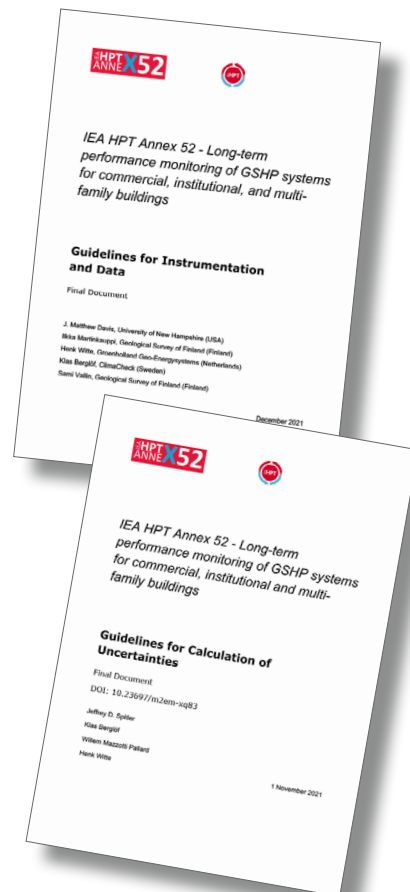


Figure 1. Two new guideline documents on instrumentation and calculation of uncertainties are completed. Illustration: Signhild Gehlin.

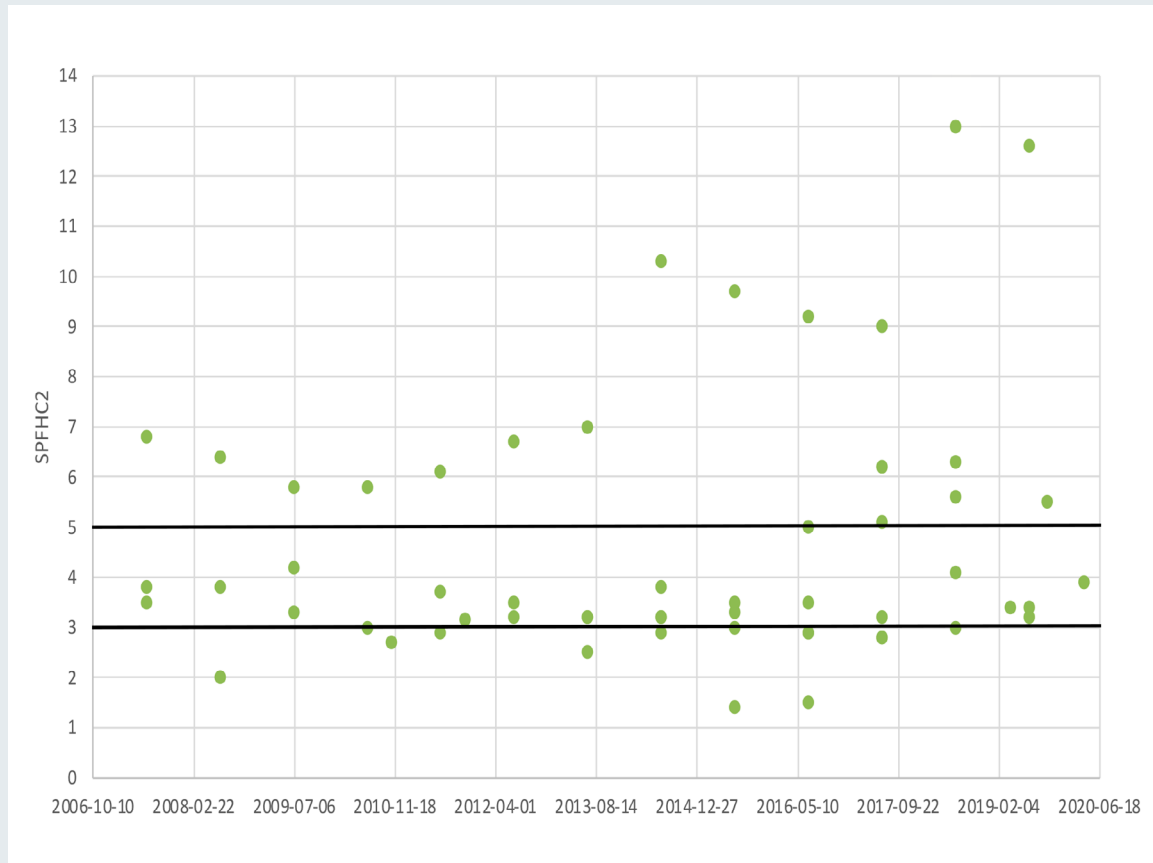


Figure 2.  $SPF_{HC2}$  for 12 projects with totally of 59 years of data. 80% of the project-years have  $SPF_{HC2}$  of 3 or higher, and 34% of the project years have  $SPF_{HC2}$  of 5 or higher. Illustration: Signhild Gehlin.

## Results

Annex 52 finished in December 2021. Two guideline documents and 21 case study reports are now published on the [Annex 52 website](#). The two new guideline documents on instrumentation and calculation of uncertainties provide valuable guidance to building owners, engineers and researchers about requirements for performance measurements, data collection and uncertainties. The 62-page instrumentation guideline presents an overview of the instrumentation that is typically required to measure the long-term performance of GSHP systems. GSHP performance studies can be conducted to meet a variety of monitoring and verification objectives and also provide data that can be used to improve system performance. Additional information is provided regarding the use of heat meters and distributed temperature sensing in GSHP studies. Challenges of data management are discussed as well as some methods to address these challenges.

Uncertainty analysis is an important tool to help understand the significance of results from any measurement

program. The uncertainty guideline is a 54-page document aimed at helping practitioners to quantitatively estimate uncertainties.

Results for 26 projects with 116 years of data in total are presented in the 21 case study reports. Not all projects can measure at the same boundaries, but 12 projects with 59 years of data have measurements for Boundary 2, which includes the ground heat exchanger and heat pump(s). Seasonal performance factors within this boundary for heating and cooling together ( $SPF_{HC2}$ ) are in the range 1.4-12.6, with an average of 4.6. 80% of the project-years have  $SPF_{HC2}$  of 3 or higher, and 34% of the project years have  $SPF_{HC2}$  of 5 or higher, see Figure 2.

A webinar presenting the overall results from Annex 52 is planned for the spring of 2022. A report on key performance indicators and an annotated bibliography will be published in the coming months on the [Annex 52 website](#).

ANNEX  
54HEAT PUMP SYSTEMS  
WITH LOW GWP  
REFRIGERANTS**Introduction**

Heat pump systems have garnered the public's attention as a renewable heating and cooling solution in the carbon-neutral world to come. Therefore, low-GWP refrigerants are considered to be used for environmentally friendly heat pump systems. Due to the unique thermophysical characteristics of low-GWP refrigerants considered, minor to major components and system design modifications are necessary for each low-GWP refrigerant. Especially, component-level design and optimizations are much needed for energy efficiency and reduced-charge designs.

**Objectives**

Annex 54 promotes the application of low-GWP refrigerants to air-conditioning and heat pump systems with the following objectives:

- » a comprehensive review of recent R&D progress on component optimization using low-GWP refrigerants (fulfilled),
- » in-depth case studies of component optimization, which can provide design guidelines and real-world experiences (fulfilled),
- » optimization of heat pump systems for low-GWP refrigerants (ongoing)
- » analysis of the Life Cycle Climate Potential (LCCP) impacts by the current design and optimized design with low-GWP refrigerants (ongoing)
- » Making an outlook for heat pumps with low-GWP refrigerant for 2030 (planned)

**Key data**

- » Project duration: Jan 2019 – Dec 2023
- » Operating Agent: Yunho Hwang, University of Maryland, College Park, [yhhwang@umd.edu](mailto:yhhwang@umd.edu)
- » Participating countries: Austria, France, Germany, Italy, Japan, Korea, Sweden, and USA.
- » Further information: All workshop presentation materials, meeting agenda, minutes, and attendee list are available from the Annex 54 website at <https://heatpumpingtechnologies.org/annex54/>

**Results**

In 2021, we achieved considerable progress in the following two areas: 1) Task 2: case studies and design guidelines for optimizing heat pump systems using low GWP refrigerants. 2) Task 3: a review of design optimization and advancement impacts on life cycle climate performance (LCCP) reduction. The work can be a valuable reference for researchers, engineers, and policymakers across the HVAC industry. The progress accomplished by participating countries is described below.

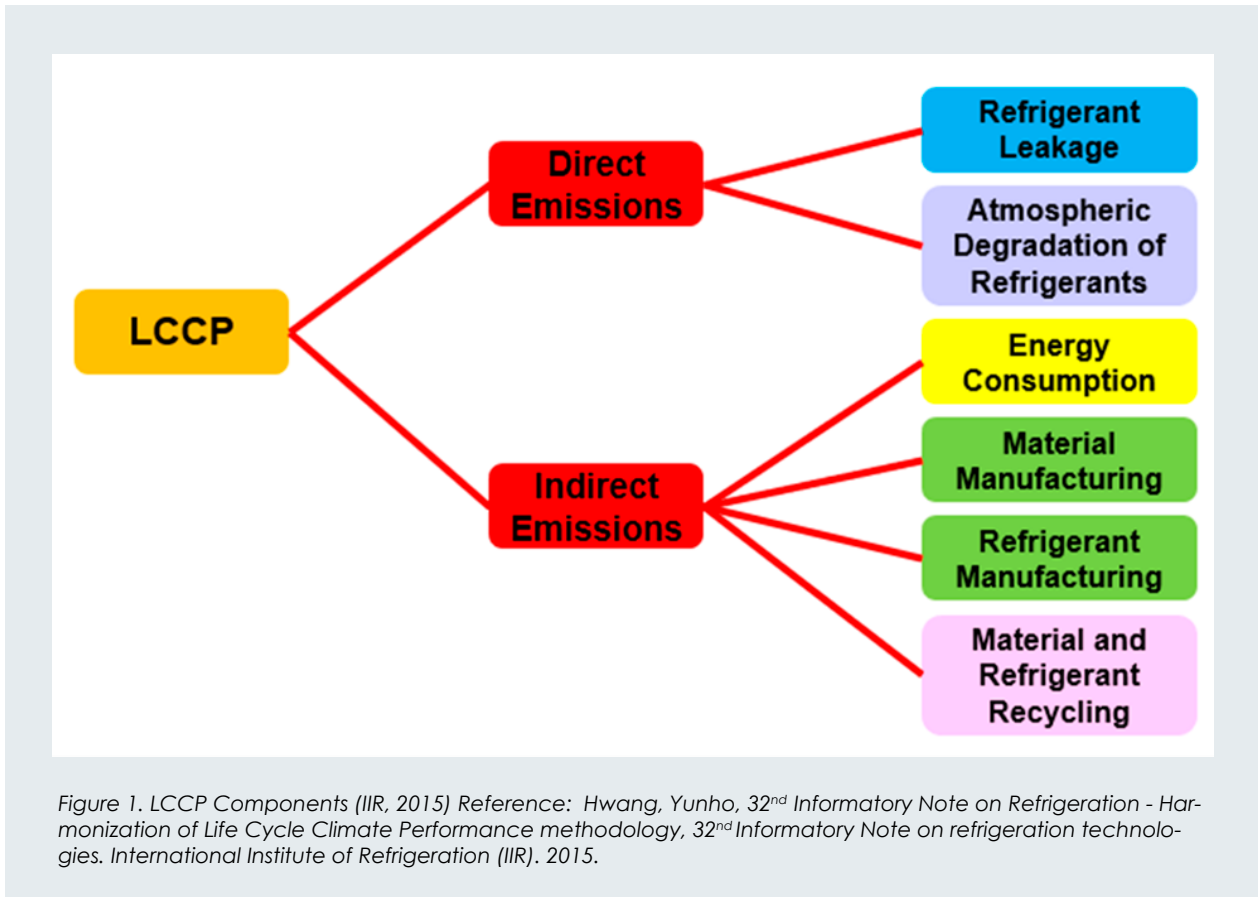
The research groups in the U.S.A. summarized the activities related to establishing a detailed database of alternative lower GWP refrigerants for various HVAC&R applications, including thermodynamic and transport properties. The goal is to identify the most suitable candidates for the replacement of traditional refrigerants based on thermodynamic performance and environmental benefits. The study also considers the extent of potential system adjustments required to accommodate the new alternative refrigerants. University of Maryland research group provided a comprehensive investigation of the LCCP of unitary air conditioners. The review focused on LCCP methodologies, impacts of parameter and methodology selections, and a few representative case studies.

The teams in Italy carried out significant advances in the use of low GWP refrigerants in heat pumps. Three research entities report their progress on low GWP refrigerants and their applications in various heat pump systems. The activities cover condensation and flow boiling heat transfer coefficients measurements and multiple experimental-oriented projects on long-term evaluations of novel heat pump systems using low GWP refrigerants.

Research groups in Japan mainly focus on the first step of a two-step process on LCCP evaluation of heat pumps with next-generation refrigerants. They also presented an overview of a project to establish a new concept and hypothesis for LCCP evaluation, in which field data related to air conditioners is adopted.

The French research group conducted studies on finned-tube heat exchangers using low GWP refrigerants. The study assessed the heat transfer performance during evaporation and condensation of R410A, R454B, and R32 in a finned-tube heat exchanger. A 30-kW experimental setup was built to assess the heat exchanger performance with these three refrigerants. The simulations show that the same design of the finned tube heat exchanger can be used for R410A and R454B, but a design optimization is necessary with R32.

Several research groups in German collaboratively summarized the most recent large-scale heat pump monitoring project, a review of ongoing heat pump projects based on an analysis of the EnArgus database, and a survey on heat pumps and their refrigerants as part of



the market incentive program coordinated at the Federal Office for Economic Affairs and Export Control. Further, they presented a high-level summary of R&D progress across multiple institutions in Germany. Within the last five years, the activities for 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 pumps systems for multi-family houses. The annual report for Annex 54 can be found on the [Annex 54 website](#).

## INFORMATION

### Do you want to read more about the results and outcome of the HPT TCP Annexes?

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# Project to develop Next-Generation Refrigerants and Refrigeration and Air-Conditioning Technology to achieve Energy Conservation and Mitigate Global Warming

Eiji Hihara, Project Leader at NEDO, Japan  
 Toru Sano, Project Manager, NEDO Environment Department, Japan

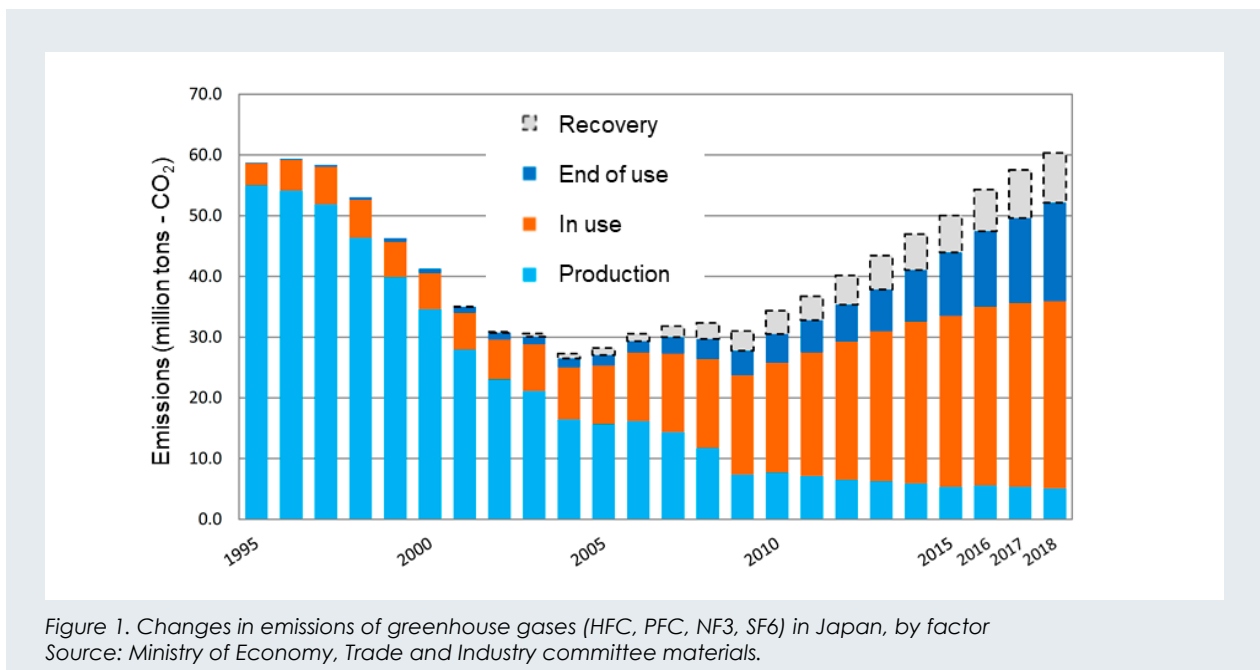
The New Energy and Industrial Technology Development Organization (NEDO) in Japan conducts research and development to establish safety and risk assessment methods for next-generation refrigerants used in commercial refrigeration and freezing equipment as well as residential air-conditioners. Support is provided for product development and the development of ultra-low GWP refrigerants to solve technical issues that hinder the practical application and dissemination of next-generation refrigerants.



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Hydrofluorocarbons (HFCs), which have been developed as alternatives to CFCs and HCFCs and pose no risk of ozone layer depletion, are used as refrigerants for refrigeration and air-conditioning equipment and foaming agents. As the conversion progresses, HFC usage and emissions are increasing. However, HFCs have been designated as an emission reduction target under the Paris Agreement because they remain stable in the atmosphere long-term and have an extremely high greenhouse effect. In addition, at the 28<sup>th</sup> Conference of the Parties to the Montreal Protocol (MOP28) held in Kigali, Rwanda's capital, in October 2016, a new revision

of the Montreal Protocol was adopted, which stipulates an obligation to reduce HFC production and consumption. The amendment requires developed countries to phase down HFC production and consumption by 85% from the 2011-2013 average by 2036. This goal cannot be achieved if existing refrigerants continue to be used. For this reason, there is an urgent need to develop refrigerants that have a minimal impact on global warming while being fit for purpose for current refrigeration and air-conditioning technologies (sometimes referred to as "next-generation refrigerants").



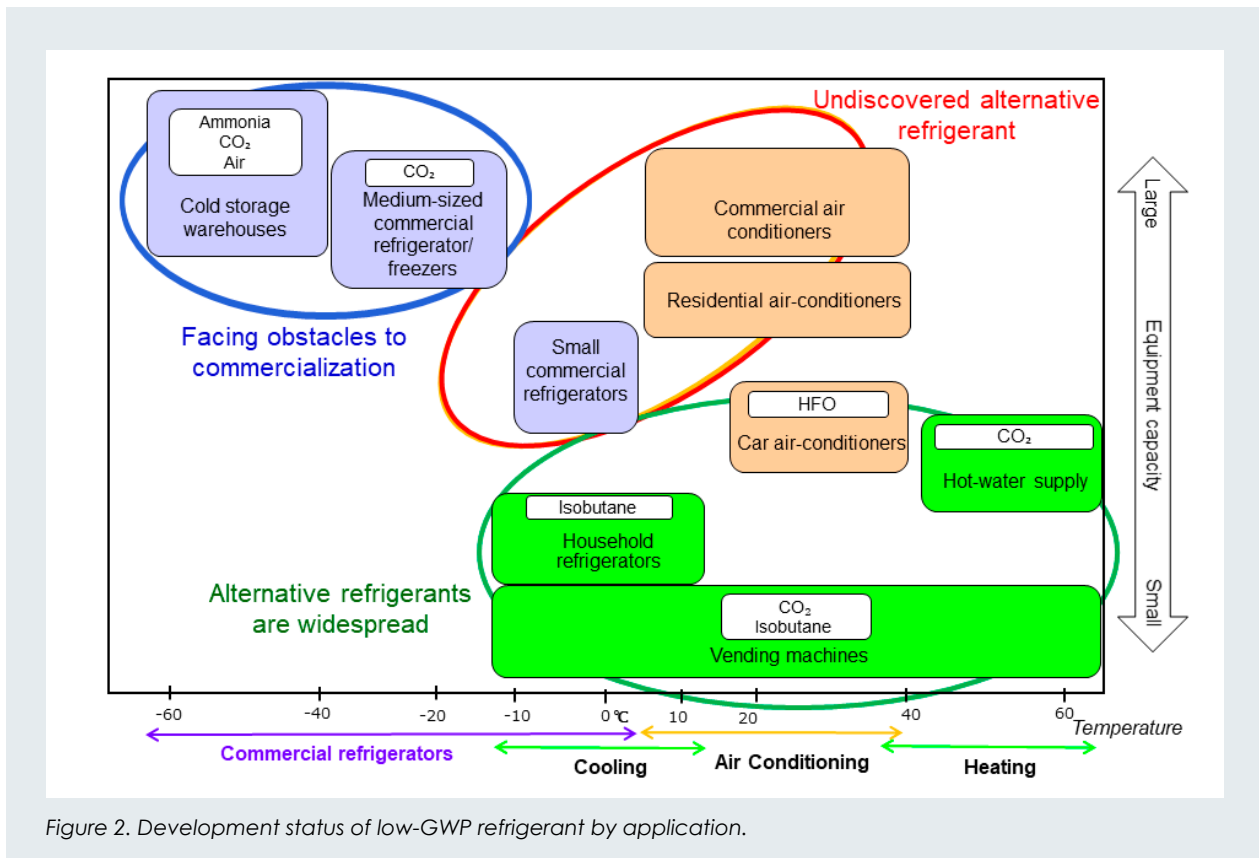


Figure 2. Development status of low-GWP refrigerant by application.

On the other hand, current next-generation refrigerant candidates face high technical hurdles to improve upon or even maintain performance equivalent to equipment using existing HFC refrigerants. They also have problems such as flammability and chemical instability. In Japan, HFC emissions account for more than 90% of emissions of the four types of greenhouse gases other than carbon dioxide. Eighty-three percent of HFC emissions come from refrigeration and air-conditioning equipment. Only 13% of the HFCs emitted from refrigeration equipment is recovered, and the rest is released into the atmosphere. Figure 1 shows four types of greenhouse gas emission sources. Emissions during manufacturing are decreasing, but emissions during use and at the end of use are increasing. Refrigerant recovery is not easy, so refrigerant conversion is an essential measure. Figure 2 shows the status of conversion to low-GWP refrigerants in Japan. Next-generation refrigerants for air-conditioning equipment and small- and medium-sized refrigeration equipment are still being sought.

Under these circumstances, in 2018, the New Energy and Industrial Technology Development Organization (NEDO) embarked on the following five-year project with the Ministry of Economy, Trade and Industry's support. In this project, we work to grasp the fundamental characteristics of next-generation refrigerants, establish safety and risk assessment methods, and work on the formulation of domestic safety standards and international standards. The aim is to contribute to the market launch of products by establishing a base for the development of

energy-saving refrigeration and air-conditioning equipment that uses next-generation refrigerants. We carry out research and development to establish a safety and risk assessment method for next-generation refrigerants used in small- and medium-sized refrigeration and air-conditioning equipment, including commercial refrigeration equipment and residential air-conditioning equipment. The project budget is 2.45 billion JPY from 2018 to 2021 (2022 budget not yet determined).

## R & D content and contractors

### 1 Elucidation of fundamental characteristics of next-generation refrigerants and development of evaluation methods.

#### 1.1 Evaluation of thermal characteristics, heat transfer characteristics, and basic cycle performance of next-generation refrigerants used in small and medium-sized refrigeration and air conditioning equipment (Kyushu University).

Kyushu University is conducting the following research on the thermophysical properties of next-generation refrigerants in cooperation with several other research institutes: critical constants, vapour-liquid equilibria, PVTx properties, surface tension, sound velocity, viscosity, and thermal conductivity. Based on the physical property values measured in this project and other research data, the equation of state for a next-generation refrigerant is being developed. The characteristics of heat transfer by condensation and evaporation of next-generation refrigerants are measured for plate heat exchangers, flat

multi-port tubes, inner grooved tubes, and smooth circular tubes.

*1.2 Safety evaluation of low-GWP, low-combustible refrigerant mixtures (National Institute of Advanced Industrial Science and Technology (AIST)).*

In this research, a mixture of a highly combustible refrigerant having three or fewer carbon atoms, such as fluoroolefin, and a low-combustible refrigerant, such as fluoroalkane, is targeted as a next-generation refrigerant for refrigeration and air-conditioning equipment. Mixtures are selected considering total GWP, boiling point difference and availability, and the mixing rules for the combustion characteristics of the refrigerants are experimentally and accurately evaluated.

*1.3 Research and development of practical evaluations for next-generation refrigeration and air conditioning technology using low-GWP refrigerants (Waseda University).*

The purpose of this research is to develop technologies capable of high-accuracy theoretical and test evaluation of the performance of air-conditioning and refrigeration equipment that introduces next-generation refrigerants. A heat transfer model, void fraction model, expansion valve model, and compressor model are being developed targeting the refrigerant's flow characteristics in the equipment. Performance test equipment for split-air-conditioners and commercial refrigerators is being constructed, and performance evaluation techniques for the equipment are being investigated. Furthermore, to predict the performance of next-generation refrigerants, a performance simulator is being developed.

## **2 Development of safety/risk assessment methods for next-generation refrigerants**

We examine the evaluation items necessary for the safety/risk assessment of flammable next-generation refrigerants and establish safety/risk assessment methods through numerical calculations, laboratory experiments, and outdoor experiments. Specifically, research including accident scenarios, refrigerant behavior during leaks, fire hazard assessments, ignition source assessments, explosion impact assessments, general hazard assessments, and allowable refrigerant charge amounts is conducted.

*2.1 Development of safety/risk assessment method for next-generation refrigerants (University of Tokyo)*

Refrigerant diffusion when a highly flammable refrigerant such as propane leaks from an air conditioner or a commercial reach-in display cabinet is numerically simulated. The maximum refrigerant charge and the stirring effects of the indoor unit fan are investigated. Research is conducted with the aim of eliminating compressor explosions caused by erroneous operation by service personnel during a split air-conditioner's pump down

operation. Some HFO refrigerants may undergo a disproportionation reaction due to an electric short circuit in the compressor in high-temperature and high-pressure conditions, leading to a compressor explosion. Research is being conducted on the suppression of disproportionation reactions.

*2.2 Establishment of physical risk evaluation method for combustion of next-generation refrigerants considering ignition sources in an actual use environment (Suwa University of Science)*

In this research, equipment and phenomena capable of acting as ignition sources are extracted when a highly flammable hydrocarbon refrigerant, expected to serve as a next-generation refrigerant, is used. The extracted ignition sources are categorized by ignition mechanism, and a model of the ignition mechanism is constructed for each category. The ignitability of a propane/air mixture is tested with contact switches, power plugs, electric sparks when opening and closing relays, static electricity, and cigarettes.

*2.3 Evaluation of full-scale physical hazards related to the combustion of refrigeration and air conditioning equipment using natural refrigerants (National Institute of Advanced Industrial Science and Technology (AIST))*

Physical hazards are evaluated in the event of rapid leakage when propane is used as a refrigerant for split air-conditioners and commercial reach-in display cabinets. In combustion impact evaluations of reach-in display cabinets, a steel simulation room is set up at the field experiment site, propane is emitted and ignited, and a combustion evaluation experiment is conducted. In evaluations of the combustion effects of split air-conditioner indoor units, an ignition test is conducted by installing a steel container at the field test site.

## **3 Research on safety and risk evaluation of next-generation refrigerants (research project)**

To efficiently link commissioned project results to industry safety standards and international standardization, we conduct trend surveys of regulations and standards. We organize committees for industry-academia-government collaboration to study the safety and risk assessment of next-generation refrigerants and disseminate the results both domestically and internationally in cooperation with commissioned projects. This research is outsourced to the Japan Society of Refrigerating and Air Conditioning Engineers.

## **4 Development of a next-generation refrigerant and its application technology**

It is crucial to solve the technical problems that hinder the practical use and popularization of next-generation refrigerants. For that purpose, we conduct subsidy projects.

*4.1 Development of a large cooling unit that utilizes natural refrigerant and ultra-low GWP refrigerant (Mitsubishi Electric Co.)*

This research aims to apply carbon dioxide, a natural refrigerant with a low environmental load, to the cooling units for large refrigerated warehouses and to develop an inexpensive and highly efficient system. The development target is to have an annual COP of 100% or more and a selling price of at most 140% the price of a 60 horsepower refrigerator using R404A refrigerant.

*4.2 Development of condensing unit technology adaptive to next-generation, low-GWP refrigerants (Toshiba Carrier Co., Ltd.)*

In this research and development, a condensing unit using a low-GWP refrigerant is being developed. A suitable refrigerant is selected from HFO/HFC mixed refrigerants. The development goal is to improve rated equipment performance to a level equivalent to current equipment and improve annual equipment performance during actual operation by 5%.

*4.3 Development of an energy-saving refrigerator system using CO<sub>2</sub> refrigerant (Panasonic Co.)*

This project aims to promote the spread of carbon dioxide as a refrigerant in the field of commercial refrigerating equipment. The refrigerator's capacity can be increased by connecting the compressor units. An air-cooled heat exchanger unit that efficiently cools even with a high outside air temperature is being developed, and a system using the exhaust heat of the refrigerator is being designed. The project aims to create a refrigerator that can be applied to medium- and high-temperature regions.

*4.4 Development of a mildly flammable refrigerant for direct expansion air conditioners with a GWP of 10 or less (Daikin Industries, Ltd.)*

This project aims to develop a refrigerant for direct expansion air conditioners with a GWP of less than 10. As a target of refrigerant performance, the coefficient of performance is set to 90% or more of the current refrigerant, R410A. Regarding flammability and toxicity of the refrigerant, ASHRAE's safety category A2L is targeted.

### Conclusion

Although next-generation refrigerants have been used in some applications, their use in other application areas has not yet become widespread. Considering the time needed for the dissemination of new technologies, to achieve the Kigali Amendment's goals, we will implement a wide range of measures based on new seed technologies and develop technologies in a variety of fields to support its dissemination as quickly as possible. It is indispensable to promote technological development for technical issues in order to overcome roadblocks to dissemination to technologies, improve efficiency, and expand the scope of application.

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## INFORMATION

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# The Future of Refrigerants for Heat Pump Applications

B. E. Badran, M. Ghanbarpourgeravi, R. Khodabandeh, Sweden

Industry and other sectors are currently looking for solutions to decarbonize their processes, including heating, which is mainly based on fossil fuel boilers. Moving to the electrification of heat by implementing heat pump technologies to provide the demanded load can be complex. Choosing the right working fluid, synthetic or natural refrigerant, with less environmental harm (low GWP) and human (safety issues) is under debate globally and is urgently needed before 2030. Some measures have been taken to solve this problem by introducing short-term synthetic refrigerants such as R32 in Europe and R454B in the US with low GWP values. This article summarizes the debate of which refrigerants are suitable for usage in heating and cooling systems and their effects on the surroundings.



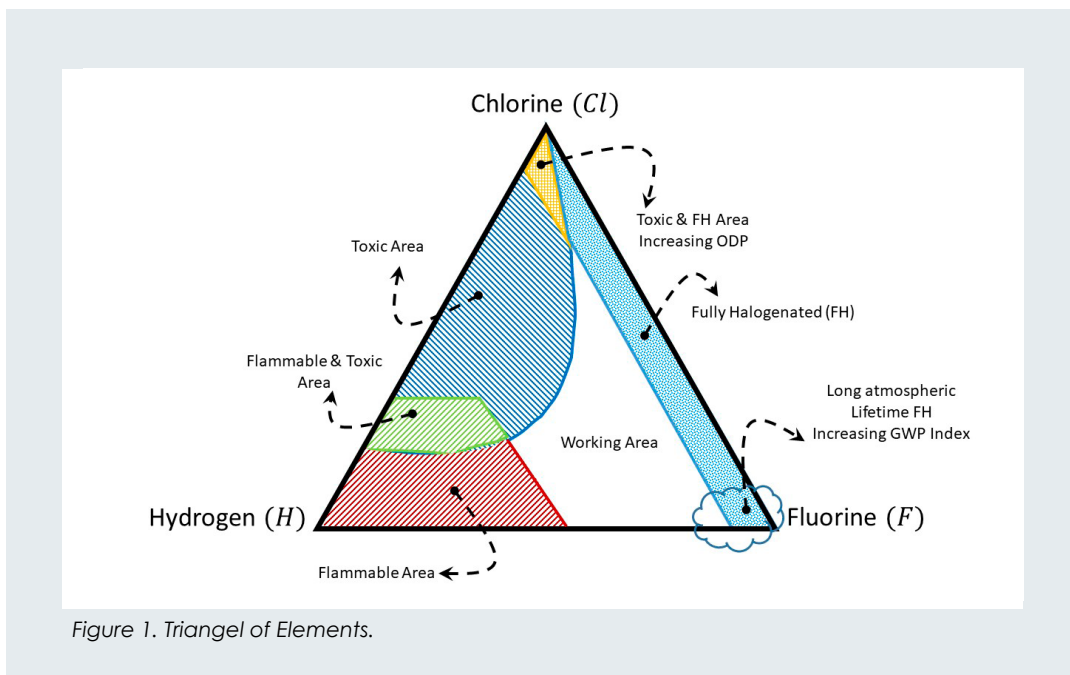
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The thirst for energy around the world is growing exponentially, especially in China, the fastest-growing economy. The U.S. Energy Information Administration (EIA) estimates that the world energy usage will increase by 50% between 2018 and 2050 (IEO 2020), which will drive the levels of Greenhouse Gases (GHGs) such as carbon dioxide and different air pollution to higher values. With the current emission rates of GHGs, the earth's temperature will rise above (2°C) by 2036, and it is by UNIPCC standards harmful, devastating, and life-threatening. The 2030 climate and energy framework at Paris Agreement in 2015 has set a binding target between EU members to reduce the emissions of GHGs by 40% between 2021 and 2030, increase energy efficiency by

32.5%, and reach climate-neutral by 2050. In Early 2021, the European Commission proposed another increase to raise the target from 40% to at least 55% (2030 Climate Target Plan) for sectors covered under the existing EU Emissions Trading System. To achieve this reduction, the phase-out of HCFC and HFC with GWP<sub>100</sub> values over 500 is necessary.

## Refrigerants' Suitable Chemical Structure.

The progress towards the HFC phasedown targets by 2030 under the Kigali Amendment is an important step to save our planet. It is very important that policymakers and industry stakeholders understand on what basis we should approach the HFC phasedown and what measu-



res we should adopt in this process. Up to date, HFCs are still in use in HVAC systems and heat pump applications. The choice for a suitable refrigerant depends on its chemical and thermal properties. Thermal factors affect the coefficient of performance (COP) and volumetric efficiency of the system, while chemical properties have important effects on the environment and on the selection of the refrigerant itself. Based on the triangle of element ([Refrigerant Selections](#)), shown in Figure 1, adding chlorine atoms to the chemical structure of the refrigerant would increase the Ozone Depletion Potential (ODP) values, increasing hydrogen atoms would elevate the flammability rates of the refrigerant, and more fluorine atoms would raise the Global Warming Potentials (GWPs) index. For example, the new refrigerant R-1336mzz(Z) with the chemical formula of (C<sub>4</sub>H<sub>2</sub>F<sub>6</sub>), which is not flammable and of low GWP value, is based on Butene, also known as Butylene, with the chemical formula of (C<sub>4</sub>H<sub>8</sub>), which is highly flammable, and six hydrogen atoms have been replaced by fluorine.

#### Refrigerants' Index Argument.

Table 1 shows some of the refrigerant's group, its GWP<sub>100</sub> values based on IPCC Sixth Assessment Report

(AR6), and its allocation in ASHRAE Safety classifications. A (low) or B (high) represent toxicity levels; and 1 (low), 2 (medium), 2L or 3 (high) represent levels of flammability. The notation A2L indicates a class 2 refrigerant with a burning velocity less than or equal to 10 cm/s. The table clearly demonstrates the tradeoff between GWP values and the flammability index. It shows that there are no non-flammable alternatives for GWP<sub>100</sub> ≤ 150. Danfoss gives a holistic flammability view based on refrigerants' densities and their GWP<sub>100</sub> values and a short way of selecting a suitable refrigerant ([Flammability Line](#)).

The GWP<sub>100</sub> values for synthetic refrigerants (CFC, HCFC, HFC, HFO) and natural refrigerants were adopted as a metric to implement the multi-gas approach embedded in the United Nations Framework Convention on Climate Change (UNFCCC), and made operational in the 1997 Kyoto Protocol. The choice of time horizon has a strong effect on the GWP values. Given that climate change signs have been observed and measured all over the world, policies based on GWP<sub>20</sub> figures could accelerate the process of reaching the targets faster and would influence the order of how the control steps are executed. Figure 2 compares the values of two indexes. One of the

Table 1. Refrigerants with their corresponding GWP<sub>100</sub> values ([AR6 IPCC](#)).

Group	Refrigerant	Safety Group	GWP <sub>100</sub> (AR6)
Natural	R-218 (Water)	A1	0
	R-717 (Ammonia)	B2L	0
	R-744 (Carbon Dioxide)	A1	1
	R-1270 (Propylene)	A3	2
	R-290 (Propane)	A3	5
	R-600a (Isobutane)	A3	4
HFO	R-1243zf	A1	
	R-1336mzz(Z)	A1	2
	R-1234yf	A2L	0.5
	R-1234ze(E)	A2L	1
HCFO	R-1224yd	A1	1
	R-1233zd(E)	A1	4

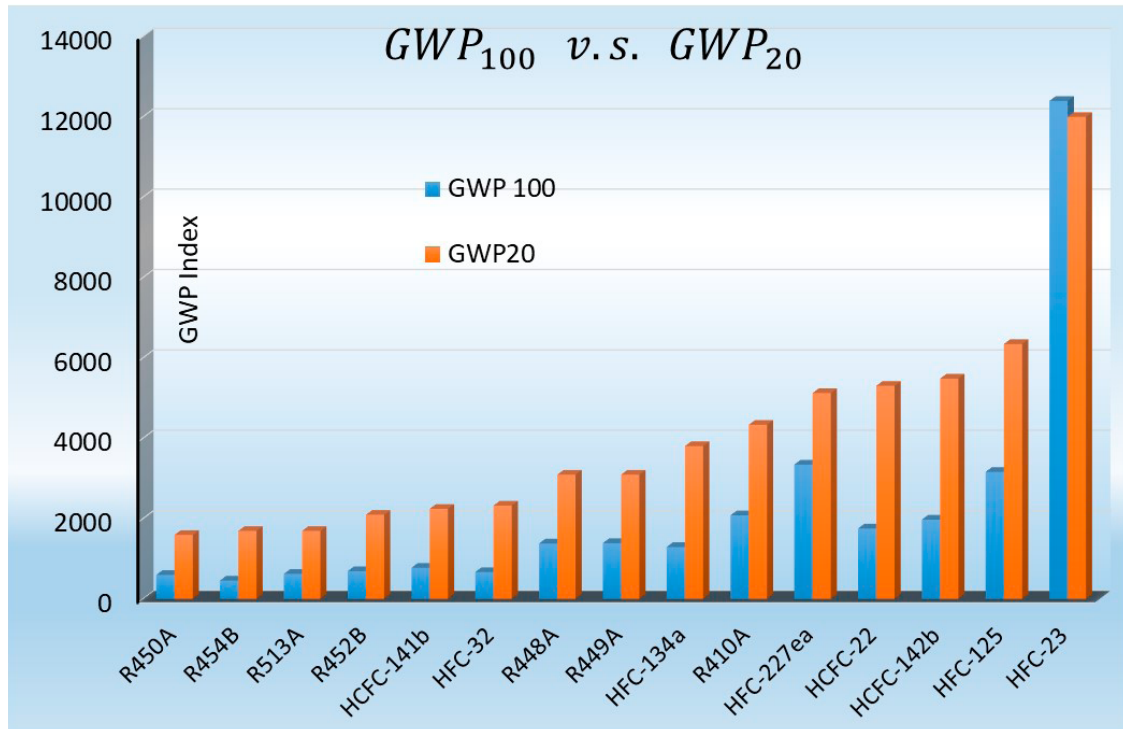


Figure 2.  $GWP_{20}$  versus  $GWP_{100}$  values.

reasons  $GWP_{20}$  values can be adopted is that the lifetime of HFCs ranges from 1.4 to 52 years and the average lifetime is 21.7 years ([HFC Contribution](#)). Not all agree with the move to the new index because the presented data over 20 years could be misleading to the public as well as policymakers in terms of which refrigerants are truly climate-friendly and sustainable. The  $GWP_{20}$  values would emphasize the removal of certain HFCs, such as R134a, and short-lived GHGs, such as methane, but would allow for a larger amount of carbon dioxide (century) and long-lived GHGs to not be reduced. This consequently will raise the earth's temperature for hundreds of years to come. It is also important to evaluate other indexes, as seen in Figure 3, the Total Equivalent Warming Impact (TEWI) and the Life Cycle Climate Performance (LCCP). TEWI is an index that assesses simultaneously the GHG emissions caused by the accidental refrigerant leakages (Direct Effects, DE) and those caused by electricity consumption during the system operation (Indirect Effects, IE). LCCP takes into account other  $CO_2$ -equivalent emissions not included in the TEWI analysis, should also be considered in selecting the right refrigerant ([Warming Impact Metrics](#)).

#### Refrigerants' Environmental Effects.

Another issue that affects the selection of a suitable synthetic refrigerant is Per- and PolyFluoroAlkyl Substances (PFAS) and its sub-groups. PFAS dissolve in drinking water, dangerous to humans if they are consumed in large quantities, and breakdown slowly in time. The Organisation for Economic Co-operation and Development (OECD) ([OECD 39](#)) identified over 4700 substances

as PFAS in their risk management report published in 2018. In the same report, they define new groups that fulfill the common definition of PFASs, which include hydrofluorocarbons (HFCs) and hydrofluoroolefins (HFOs) refrigerants. In the atmosphere, some of these refrigerants breakdown because their chemical formula contains double bonds, which makes their molecules less stable. The result of the decomposition is a TriFluoroacetic Acid (TFA) which is yet another sub-group of PFAS. Table 2 shows some synthetic refrigerants with their TFA yield. The European FluoroCarbons Technical Committee (EFCTC), which provide an up to date information about applications, safety, health and environmental effects for HFCs, HCFOs, and HFOs, does not classify these gases to meet the criteria of Persistent, Bioaccumulative, and Toxic substances (PBT), and it claims that these gases pose no harm to the environment. We should not be alarmed by PFAS or TFA now because they already exist in small amounts in food packaged; commercial household products such as water-repellent fabrics, nonstick products (e.g., Teflon), and so forth ([PFAS Explained](#)), but the breakdown of fluorocarbons mentioned before would increase their dosages in the environment. EU REACH Regulation from the European Chemical Agency (ECHA) said, "Without taking action, [PFAS] concentrations will continue to increase, and their toxic and polluting effects will be difficult to reverse."

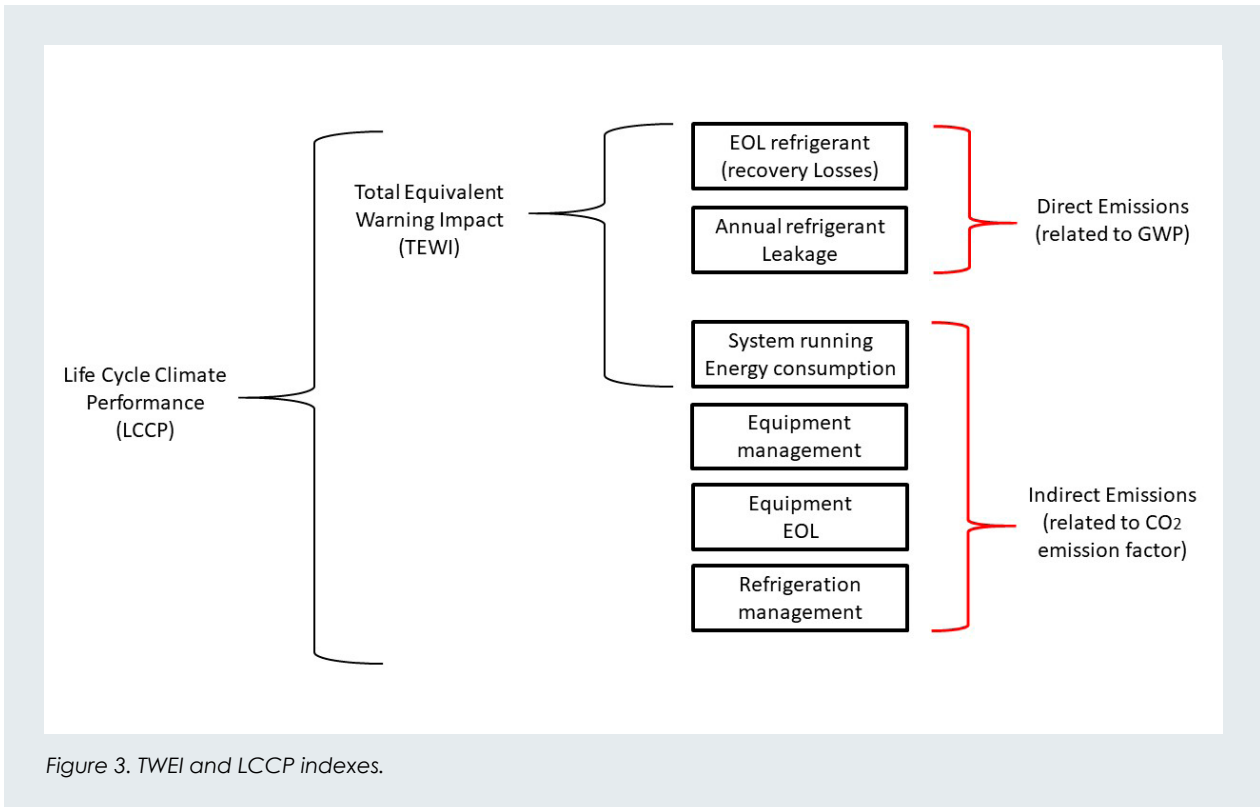


Figure 3. TEWI and LCCP indexes.

Table 2. TFA Yield of Fluorocarbon Synthetic Refrigerant ([F-gas Breakdown](#)).

Refrigerant	TFA Yield
HFC-134a	21%
HFC-245fa	Less than 10%
HFO-1234ze(Z)	0%
HFO-1234yf	100%
HFO-1336mzz(Z)	4%
HCFO-1233zd(E)	0%

**Conclusions**

We are still debating how to address the problem of limiting the rise in global temperatures, and time is passing by as we fail to take drastic actions to halt this trend. Natural refrigerants may be viable answers for the current challenges, but they are flammable and/or toxic, although extra design measures and safety requirements could help us avoid these issues.

The industry is technically ready to replace high-GWP refrigerants with new synthetic refrigerants with low GWP values, but compatibility issues such as compressor oil, thermal performance characteristics, and their impact on the environment and humans must be

addressed. The time to save our planet is running out, and we need to find a solution to this vague picture as soon as possible.

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# Who Wants to Be a Millionfold Deployed Refrigerant?

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Heat pumps are a key technology to accelerate the defossilization of all sectors. Especially in residential applications, heat pumps serve as exchange technology for conventional heating technologies. The operation of heat pumps requires a refrigerant that significantly determines the system's efficiency. However, the refrigerant choice is complex due to interactions with all components and nonlinear thermodynamic behavior. Therefore, refrigerant selection is widely discussed in the literature. This work introduces the refrigerant selection problem and applies a simple screening method to identify proper refrigerants in residential heat pumps. The application reveals future work to improve the refrigerant selection aiming for the optimal refrigerant in heat pumps concerning their application.



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The building sector in Germany currently comprises around 19 million buildings. In nine out of ten cases, the heat supply of these buildings is based on the combustion of oil and gas in conventional heating systems [1]. The combustion yields that 30% of total CO<sub>2</sub> emissions in Germany are attributable to the building sector, with almost 80% of these emissions being emitted in the provision of space heating and domestic hot water [2]. Reducing emissions of greenhouse gases (primarily CO<sub>2</sub>) in the building sector is an essential pillar of the German government's comprehensive program to achieve Germany's climate targets.

The heat pump is an alternative, efficient and sustainable technology to supply a building with heat. Unlike conventional heating systems, the total emissions of a heat pump are differentiated into direct and indirect emissions. The direct emission results from the refrigerant used and the respective filling quantity. The lower the GWP and the refrigerant charge, the lower the direct emissions in the event of a leakage. On the other hand, indirect emissions result from electricity to drive the heat pump. Especially when the electricity used has a high share of renewable energy or is generated with highly efficient power plants, heat pumps lead to primary energy savings and thus to a reduction in emissions in general [3]. Furthermore, indirect emissions decrease if the heat pump's efficiency is increased. Basically, the higher the efficiency, the less electricity must be used to provide heat, whereby the efficiency strongly depends on the selected refrigerant.

Today, the most widely used refrigerants belong to the fluid group of fully or partially halogenated hydrocarbons (HCFC and HFC). Fully or partially halogenated hydrocarbons are non-flammable and also considered safety refrigerants. Furthermore, they have no ozone depletion potential (ODP value: "Ozone Depletion Potential") and are characterized by good thermodynamic

properties. However, despite their advantages, HCFCs and HFCs are criticized for their very high GWP and will have to be replaced by more environmentally friendly refrigerants in the long term. In this regard, EU Regulation No. 517/2014 [4] provides a roadmap that regulates the gradual reduction of the sales volume of hydrofluorocarbons in the future. Thus, only refrigerants with a low GWP may be used in the future, leading to refrigerant selection problems.

## Requirements for Refrigerant Selection

The choice of refrigerant is complex due to interactions in the process and thermodynamic nonlinearities. In addition, an enormous number of potential refrigerants and their mixtures exist, which must meet a variety of requirements see Figure 1. Essentially, these requirements can be divided into three areas: political (1), thermodynamic-technical (2), and economical-ecological (3).

### 1. Ever-increasing political requirements for refrigerants

Refrigerants with an ODP have been banned since the 1990s by resolutions based on the Montreal Protocol [5]. With the European F-Gas regulation, a gradual reduction of the sales volume of fluorinated by 79% until 2030 is currently being implemented [4]. Since 2020, the reduction amount has increased to 55% compared to 2015. In addition, bans on refrigerants with high GWP are being successively enacted for defined applications for specific filling quantities and refills. In order to offer sustainable and legally compliant heat pumps for the provision of heat for residential buildings in the long term, only refrigerants with a GWP of 150 or less should be used in the future.

### 2. Thermodynamic-technical requirements for refrigerants

Refrigerants have to fulfill many, partly conflicting thermodynamic-technical requirements despite the increasing political constraints. Refrigerants must generally be thermally and chemically stable [6]. Furthermore, the

refrigerant must be sufficiently soluble in oil. Otherwise, sufficient lubrication of the compressor cannot be ensured. In addition, both the temperature and pressure levels must be suitable for the respective application. For example, a refrigerant should not be operated below atmospheric pressure. Low-pressure levels can lead to seal failure or unwanted diffusion of outside air into the circuit, which significantly reduces efficiency. Finally, a refrigerant should not be toxic to humans, especially in residential applications.

### 3. Economical-ecological requirements for the future

Last but not least, there are economical-ecological requirements. As already described, one of the most influential parameters of a heat pump is its efficiency in energy conversion. Despite the limitations mentioned above, the efficiency of a heat pump must not be negatively affected by a change of refrigerant, as this reduces the potential to be a sustainable technology. For example, although it is comparatively easy to reduce direct emissions, which occur in the event of refrigerant leakage. Changing the refrigerant to a low GWP refrigerant can also reduce the indirect emissions of a heat pump. At the same time, however, the indirect emissions of a heat pump can increase dramatically due to increased electricity consumption at a lower efficiency. A lower efficiency applies analogously to the costs and emissions, depending on the electricity. In addition, the cost of the refrigerant should be low not to inhibit the market penetration of heat pumps.

### Automated Refrigerant Selection for a Residential Application

Due to the enormous number of requirements, which can often be simultaneous and partly nonlinear and opposing, a fully automated methodology has been developed at the Institute for Energy Efficient Buildings and Indoor Climate, which allows a rigorous investigation of the refrigerants under given boundary conditions. First, the refrigerants are automatically examined, filtered, and thus preselected according to the various requirements. Then, after the preselection, a detailed analysis

of the heat pump circuit is performed to provide an evaluation of the refrigerants. For a simplified illustration of this methodology, the refrigerant selection is presented below using the example of an air-to-water heat pump to provide space heating and domestic hot water.

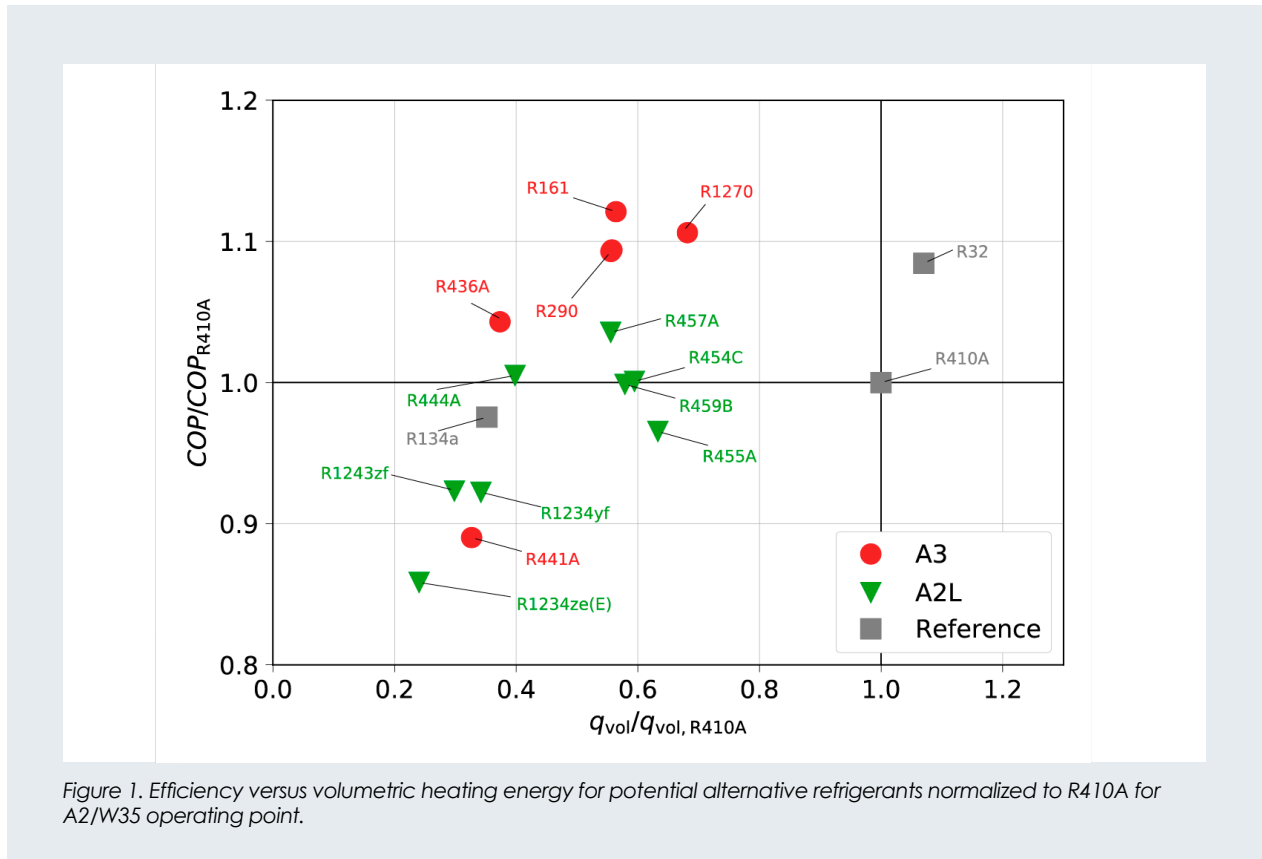
For refrigerant selection, the boundary conditions for the system to be designed must first be defined. The boundary conditions used in the presented study are shown in Table 1. Within the first preselection, the general properties of the refrigerant are checked. A maximum permitted GWP of 150 is used. Furthermore, the refrigerant must not have an ODP. Concerning flammability, all levels of the ASHRAE classification - from 1 (non-flammable) to 3 (highly flammable) - are permitted. However, the preselection process excludes toxic refrigerants, such as ammonia. The safety class summarizes these aspects (A: non-toxic, B: toxic).

Limit values of the operating range are checked. For this purpose, minimum and maximum operating temperatures and pressures are defined, which can occur during operation. For the provision of domestic hot water, condensation temperatures of up to 70 °C can occur to enable thermal disinfection. At the same time, due to maximum operating pressures above 50 bar, the durability of most materials will be shortened. The lower limit for the evaporation temperature in this study is -20 °C, which represents a cold winter day in Germany. At these cold temperatures, the system must continue to operate at positive pressure, as described initially. Therefore, a minimum operating pressure of 1.1 bar is assumed.

After preselection, a cycle calculation is performed, based on which various parameters such as efficiency (COP) and volumetric heating capacity ( $q_{vol}$ ) are calculated [7]. The cycle calculation is based on a validated compressor model [8], and an additionally implemented optimization process so that the maximum efficiency at a defined operating point is calculated individually for each refrigerant. For this purpose, the optimal pressure levels in the condenser and evaporator and the optimal

Table 1. Boundary conditions used for the study

GWP <sub>max</sub>	150
ODP <sub>max</sub>	0
Safety classes	A1, A2L, A2, A3
Minimum evaporation temperature	-20 °C
Minimum operating pressure	1.1 bar
Maximum condensing temperature	70 °C
Maximum condensation pressure	50 bar



superheat level at the compressor inlet and subcooling after the condenser are determined. Various constraints are used to ensure physically and technically feasible behavior. In addition to considering the secondary fluids (in this case, air and water), this also includes compliance with minimum superheating and subcooling and compliance with the second law of thermodynamics.

Furthermore, the calculation ensures that the optimum operating conditions for each refrigerant are guaranteed for an operating point. This setup allows a comparison of the refrigerants.

**Refrigerant Selection and Conclusions**

The presented method is applied in the following 268 fluids available on the market and belongs to the common RefProp database [9]. With the help of the various selection stages, the number is reduced to 31 fluids, which fulfill both the political and the operational specifications for air-water heat pumps [10]. Among them, only refrigerants of safety classes A2L to A3 are included. Non-flammable refrigerants of safety class A1 cannot meet either the political specifications or the technical requirements for an air-to-water heat pump in the future. However, it should be noted that CO<sub>2</sub> was not included in this study due to its supercritical operation.

Figure 2 shows the results for currently commonly used refrigerants. The heat pump's efficiency over the volumetric heating energy is shown, both normalized to a comparison process with R410A refrigerant for the other

candidates. Further, R32 was used as a benchmark in the study since it is currently used in some systems. It is noticeable that none of the alternative refrigerants reaches the volumetric heating capacity of R410A or R32. This non-achievement is because both refrigerants are high-pressure fluids mainly used in refrigeration. Due to the high pressure, there is a higher density at the compressor inlet, which positively affects the delivered mass flow and thus the heat capacity in the condenser. Consequently, future heat pumps using alternative refrigerants will have to be equipped with larger components to provide the same heat capacity.

In addition, it can be shown that the A3 refrigerants tend to have higher efficiencies. Compared to HFOs (A2L), the natural refrigerants (A3) considered here achieve up to 20% higher efficiencies. It is also interesting to note that the development of blends - here using R454C as an example - can positively affect the potential of a refrigerant in a basic heat pump cycle. By blending a high-efficiency fluid (R32) and a low-GWP fluid, the overall properties can be adjusted to meet policy requirements and increase heat pump efficiency. However, even the blend shown still delivers efficiencies about 10% lower than propane, for example, at a moderately higher volumetric cooling capacity.

Overall, the question remains which refrigerant should be a millionfold used refrigerant in the future. Natural refrigerants show proper behavior for air-to-water heat pumps - at least on a thermodynamic level. Compared

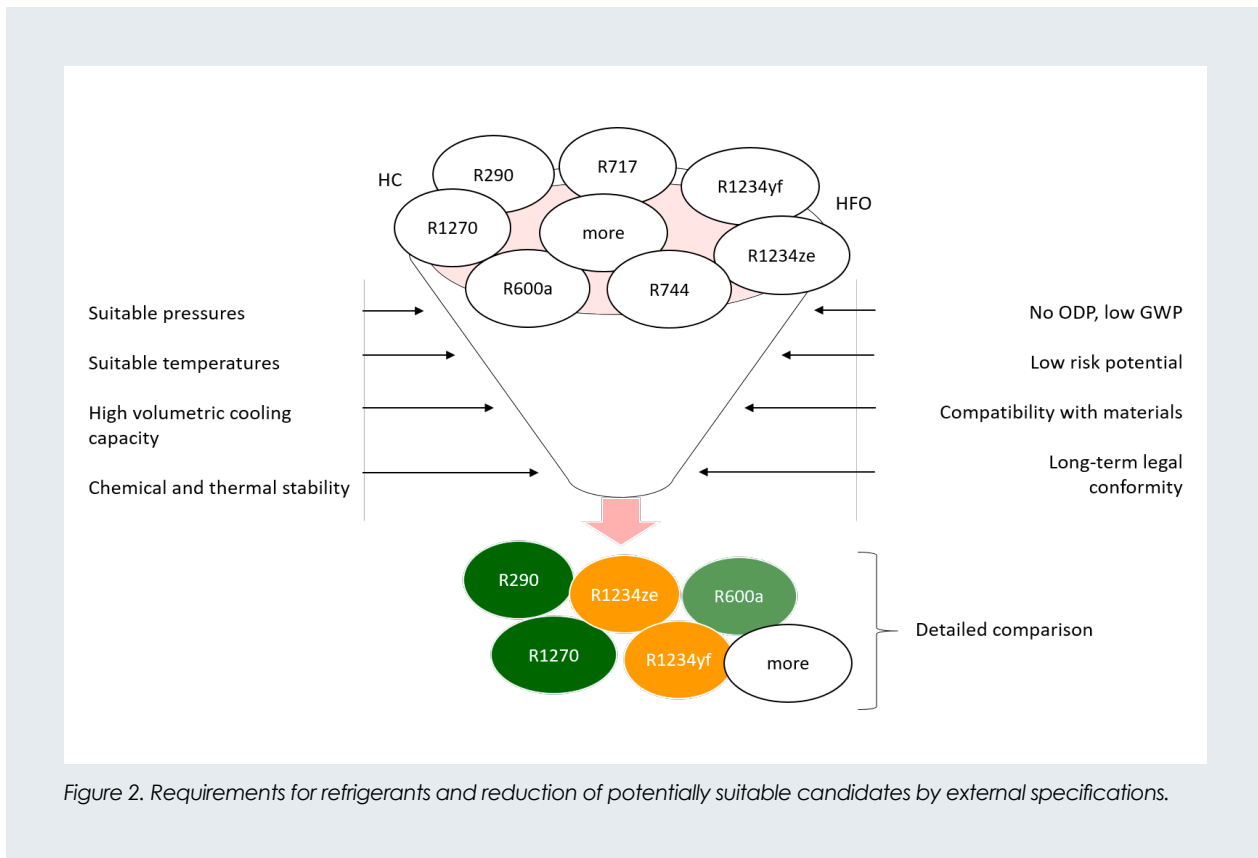


Figure 2. Requirements for refrigerants and reduction of potentially suitable candidates by external specifications.

to HFOs, higher efficiencies can be achieved using HCs. Higher efficiency reduces the overall power consumption and thus indirect emissions. In addition, higher volumetric heating capacities can, in principle, be achieved. A higher heating capacity has a positive effect on the size of the individual components and can thus be economically advantageous. Furthermore, natural refrigerants are also cheaper to procure than HFOs due to their high availability.

Ultimately, HFOs released into the atmosphere form trifluoroacetic acid (TFA for short) during their degradation process. TFA is highly soluble in water and is difficult to degrade. After TFA is formed in the atmosphere, it can enter groundwater via precipitation. It can no longer be removed from the water by conventional purification methods, thus contaminating the groundwater. Therefore, the Federal Environment Agency in Germany has already issued a recommendation in 2019 to minimize the use of TFAs [11]. However, it is questionable whether this recommendation will be formulated into political guidelines within the next few years, which is why the long-term use of HFOs is at least uncertain.

Within this study, we show that under current boundary conditions, the advantages of natural refrigerants outperform synthetic refrigerants, which is why it seems

sensible to promote them. However, choosing a suitable natural refrigerant depends strongly on the application. For example, propane and propene's pure substances showed excellent results for air-to-water heat pumps in residential applications. Propane delivers about 10% higher volumetric heating capacities. Thus, to continue accelerating the sustainable use of heat pumps, the theoretically best refrigerants must be selected under given boundary conditions and transferred to practice. The presented methodology supports this process and will be further developed regarding mixtures, refrigerants cycles, and boundary conditions.

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# Optimization of Residential Air Source Heat Pump using Low-Global Warming Potential Refrigerants

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Low-global warming potential refrigerants can significantly reduce the direct emissions of CO<sub>2</sub> originating from HVAC systems. However, high-efficiency systems are needed to reduce indirect CO<sub>2</sub> emissions. In this study, an R 410A residential 5-Ton heat pump was optimized using R 32, R 454A, R 454B, R 454C, and R 455A. Among these options, R 455A and R 454C have the lowest global warming potential but have lower volumetric capacity and high glide. Optimization results using 5 mm tube heat exchangers showed 12.4% to 19.1% efficiency improvements and 13% to 33% reduction in CO<sub>2</sub> emissions.



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Environmental concerns have driven refrigerant changes since the 1980s. The Montreal Protocol (1987) affected chlorine-containing refrigerants, and the Kigali Amendment (2016) addressed global warming concerns by restricting the use of high-global warming potential (GWP) refrigerants.

The options to replace R-410A have been reduced by these measures, and replacements are mostly non-azeotropic blends with large temperature glide. Among the alternatives, R-32, R-454B, and R 454A are near-term options with GWP <750. Long-term options would likely have GWP <150, which requires the use of high-glide blends such as R-454C and R-455A (Table 1). These refrigerants have also lower volumetric capacity and pressure. Therefore, they will require significant changes to heat exchanger (HX) designs. Therefore, this study focuses on optimizing the whole system by employing HXs with smaller diameter (5 mm) and optimized circuitry.

## System Model and Baseline Reversible Heat Pump

The US Department of Energy's Oak Ridge National Laboratory's Heat Pump Design Model [1] was used to simulate the performance of heat pumps. This model has

been validated using experimental data [2]. REFPROP 10.0 [3] was used to calculate refrigerant properties. To ensure proper simulation of 5 mm tube HXs, air-side correlations that were developed for small-diameter tubes [4] were implemented. For the 9 mm R-410A baseline system, a model from Wang et al. [5] was used.

To compare the refrigerants, a residential 5-Ton R-410A reversible heat pump is used as a baseline. Table 2 lists the parameters of the baseline HXs, including airflow rate and fan power. The indoor HX is a 3-row/72-tube coil with 8 circuits. The outdoor HX is a 2-row/96-tube coil with 8 circuits.

## Optimization Methodology

The particle swarm optimization algorithm implemented in GenOpt [6] was used to optimize the heat pump. This optimization has two objectives: the first is to maximize the efficiency at AHRI Standard cooling test A condition [7], and the second is to minimize the HX material cost. The number of circuits in indoor and outdoor HXs is a variable. The number of tubes is also a variable, which means that the number of circuits has a self-adaptive upper limit instead of a fixed upper limit.

Table 1. Characteristics of refrigerants investigated in this research

Refrigerant	GWP	Safety class	Composition and mass fraction (%)	Glide (°C)	Critical temperature (°C)
R-410A	2,088	A1	R32/R125: 50/50	0.1	72.8
R-32	675	A2L	R32: 100	0	78.1
R-454B	466	A2L	R32/R1234yf: 68.9/31.3	1.3	77
R-454A	238	A2L	R32/R1234yf: 35/65	6.2	78.9
R-454C	146	A2L	R32/R1234yf: 21.5/78.5	6.0	82.4
R-455A	139	A2L	R32/R1234yf/CO <sub>2</sub> : 21.5/75.5/3	6.9	90.2

Table 2. Parameters of indoor and outdoor heat exchangers of the baseline 5-Ton two-stage (staged at 100% and 67% compressor displacement volumes) heat pump.

Parameter	Indoor HX	Outdoor HX
Face area (ft <sup>2</sup> )	3.6	33.7
Number of tubes	72	96
Number of rows	3 (cross-mixed flow)	2 (cross mixed-flow)
Number of circuits	8	8
Fin type	Slit	Slit
Fin density (fins/ft)	168	276
Tube outside diameter (mm)	9.52	9.52
Tube horizontal spacing (mm)	25.4	22.0
Tube vertical spacing (mm)	25.4	25.4
Fan airflow rate (CFM)	1,770	4,215
Fan power (W)	478	181

In terms of operating conditions, the evaporator superheat was fixed. The condenser subcooling was automatically adjusted, but it was constrained between 1.1 °C and 8.3 °C. The cooling capacity matched the original 5-Ton R-410A heat pump by modifying the compressor volumetric displacement.

The HXs have the same frontal shapes as the baseline HX, so they can fit into the original indoor and outdoor fan-coil unit. The HX circuitry mimics a counter-flow configuration, which shows significant advantages for high-glide mixtures. The HX material cost was estimated by performing a material inventory for the copper and aluminium and multiplying them by the market price.

### Optimization Results

Figure 1 shows the results for R-410A and all alternative refrigerants. The horizontal axis depicts the Energy Efficiency Ratio (EER), while the vertical one shows the material cost of the heat exchangers. The optimal R-410A 5 mm tube design shows good performance, as expected. This performance point is also plotted on other Pareto fronts as a solid black hexagon.

R-32 results (Figure 1b) show good performance, as expected, because of its good thermal properties. On the other plots (Figure 1c–3f), reference points were set. The red triangle represents the baseline R-410A system using 9 mm tube HXs. The yellow hollow circle represents a drop-in simulation using the baseline system. The green diamond symbol represents a drop-in simulation replacing the 9 mm tubes with 5 mm tubes. The purple rectangle symbol represents a design in which the 9 mm tubes are replaced with 5 mm tubes but doubling the number of tubes.

The drop-in comparison (red triangle with yellow hollow circle) shows decreased efficiency for all alternative refrigerants. Replacing the 9 mm tubes with the 5 mm tubes (yellow circle with green diamond) shows an even greater decrease, as expected by the reduced heat transfer area. Furthermore, doubling the number of tubes (pur-

ple rectangle with green diamond) shows that increasing the HX area without optimization also fails to deliver a satisfactory solution. This analysis demonstrates the excellent sensitivity of the heat pump design model and emphasizes the need to perform optimization of the 5 mm tube system for all low-GWP alternatives.

Finally, the optimized systems (blue circle with red triangle) show significant HX cost savings and efficiency improvement compared with the baseline R-410A 9 mm tube system. The maximum efficiency improvements for low-GWP systems range from 11.7% to 14.1%, and the optimized HX design can save material costs by at least 62%, depending on the choice of refrigerants.

### Performance of Optimized Heat Pump Designs

The seasonal energy efficiency ratio (SEER) and heating seasonal performance factor (HSPF) were calculated for the optimized systems, according to AHRI 210/240 test standards [8]. In all cases, the volumetric displacement was adjusted to match the baseline cooling capacity. The performance degradation owing to frost accumulation was considered by applying performance degradation factors (0.91 for heating capacity and 0.985 for power consumption). Figure 2 shows performance for the R-410A baseline system and low-GWP optimized systems with SEER over 16 and HSPF over 9.5.

Figure 3a shows the optimized systems charges with reductions ranging from 13% to 50%, likely because of the use of optimized 5 mm tube HXs. However, compressor displacements are larger than in the baseline, indicating the need for further development.

### Life Cycle Climate Performance Analysis

Life cycle climate performance (LCCP) evaluation [8] was performed to analyze the direct and indirect greenhouse gas emissions of the system. To evaluate the annual energy consumption, each system was evaluated two cooling conditions and three heating conditions according to AHRI 210/240 test standards [8]. Other values used

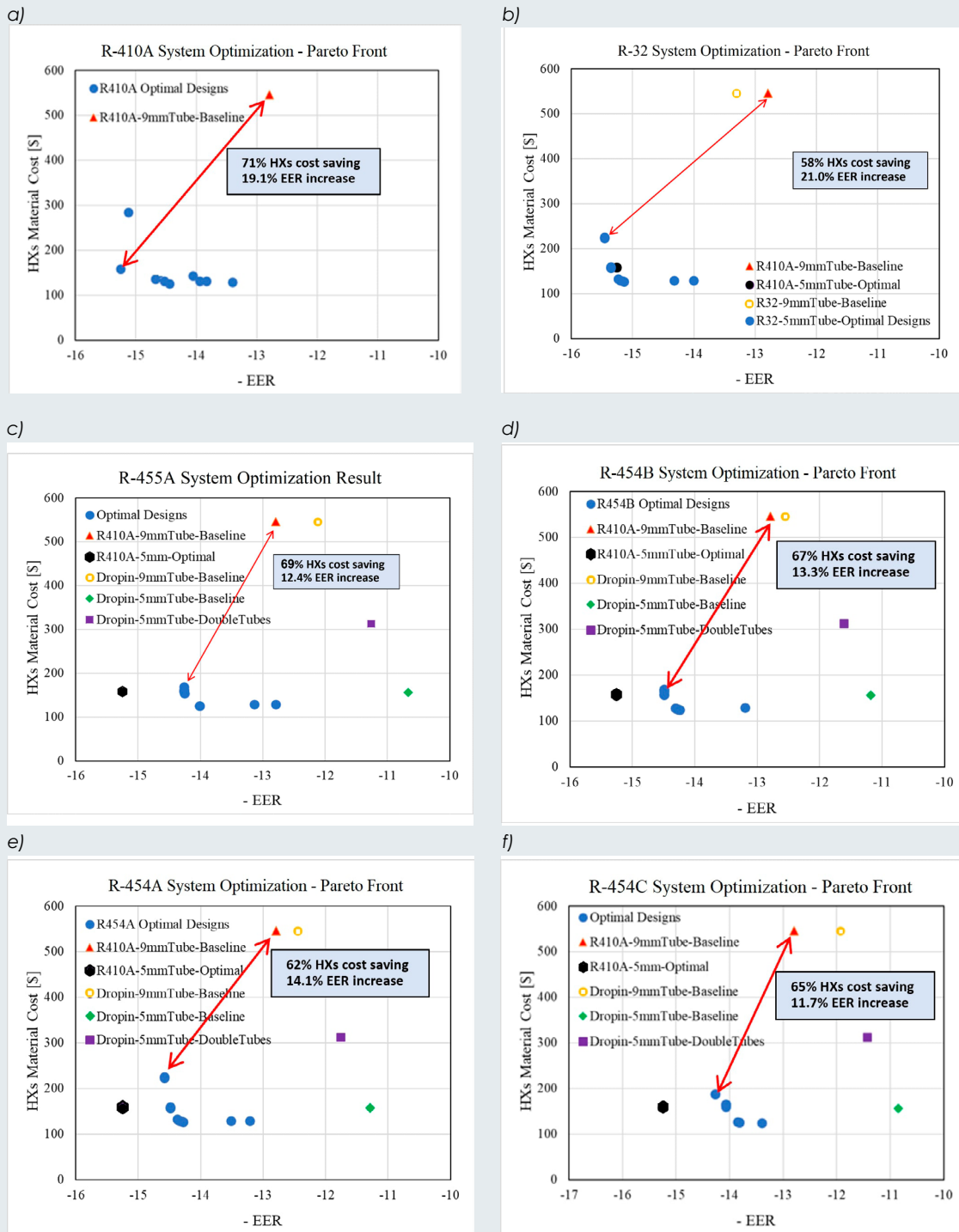


Figure 1. Pareto Fronts for 5 mm diameter tube heat pump system optimization using (a) R-410A, (b) R-32, (c) R-455A, (d) R-454B, (e) R-454A, and (f) R-454C.

for evaluating the LCCP are shown in Table 3. The cut-off outdoor temperature and the temperature at which the heat pump starts are also shown.

Figure 4 shows LCCP results for five cities representing all climate zones in the United States. The optimized systems using low-GWP refrigerants reduced total lifetime greenhouse gas emissions by 13% to 33%, depending on the refrigerant and climate zone.

**Conclusions**

This study presents heat exchanger and system development technologies to support the transition to refrigerants with GWP lower than 150. High-efficiency levels in cooling (SEER over 16.0) and heating modes (HSPF over 9.5) were achieved by a model-based design optimization approach for low-GWP refrigerants using 5 mm tube heat exchangers. The potential to reduce the overall lifetime emissions of CO<sub>2</sub> by 13% to 33% was also shown.

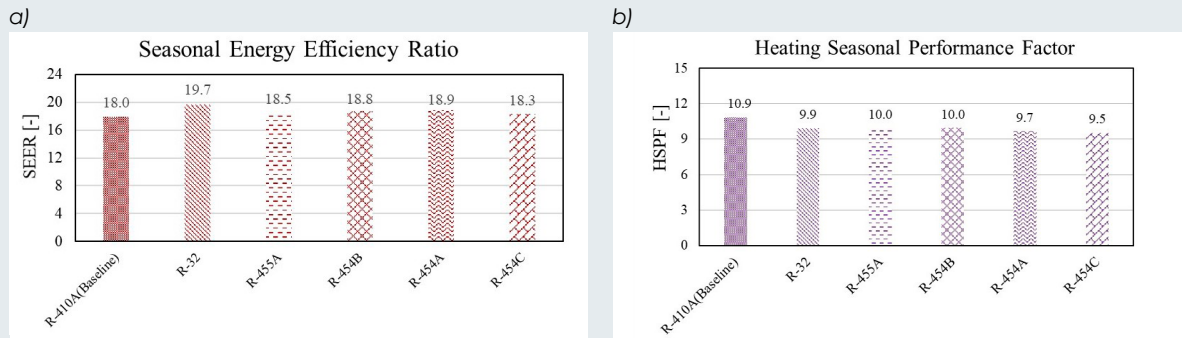


Figure 2. Performance of sampled optimized heat pump systems using different refrigerants: (a) SEER and (b) HSPF.

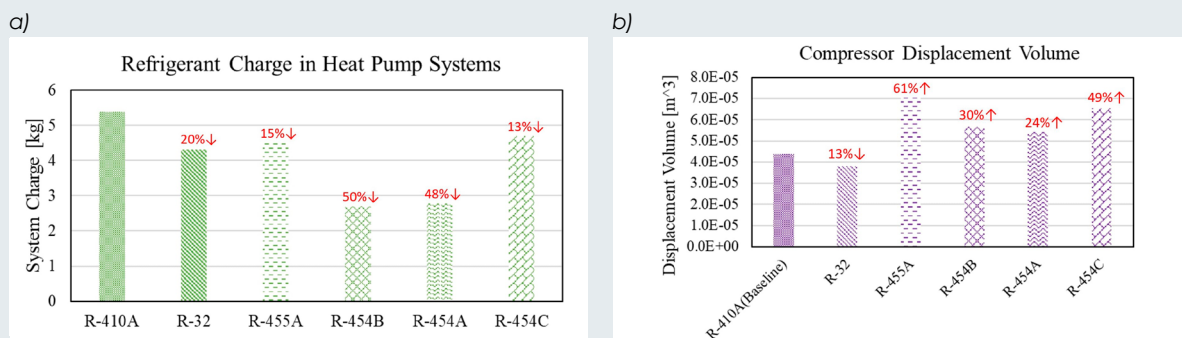


Figure 3. (a) System refrigerant charge and (b) designed compressor displacement volume.

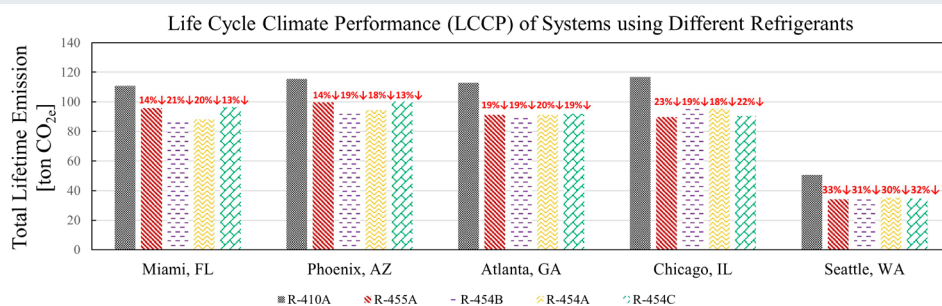


Figure 4. Total greenhouse gas emissions of the baseline system and low-GWP optimized systems.

The optimal 5 mm tube heat exchangers obtained from this research can fit into the original R-410A system frame, which helps to minimize changes in manufacturing and installation, thus reducing impacts on manufacturers

and end-users. The proposed approach establishes a production and installation path to produce cost-effective low-GWP reversible heat pumps.

This study has clearly shown the usefulness of Artificial Intelligence, i.e., optimization, in designing the next generation A/C systems. Still, significant challenges remain as other components like the compressor will also need to be properly designed for the new low-GWP refrigerants.

Table 3. Input values for baseline system LCCP calculation

Factor	Value
Refrigerant	R-410A or its alternatives
Refrigerant charge (kg)	From Figure 3 (a)
Unit weight (kg)	190
Annual refrigerant leakage (%)	4
EOL leakage (%)	15
Lifetime (years)	15
Cut-off temperature (°C)	-17.8
Temperature at which the heat pump starts (°C)	-12.2

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# Reversible CO<sub>2</sub> Heat Pump with Ejectors for Efficient Heating and Air-Conditioning

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A renowned shopping centre in the area of Lucerne, Switzerland, was modernised in 2019/2020. In this context, the existing fossil heating and air conditioning system was replaced by two reversible air-to-water CO<sub>2</sub> heat pumps with ejectors. The two heat pumps cover a heating capacity of 1.1 MW and an air conditioning capacity of 1.3 MW. Higher investment and life cycle costs were accepted in order to develop sustainable and forward-looking technologies with natural refrigerants. The project was supported by the Swiss Federal Office of Energy. Since the commissioning of the heat pumps, their operation has been investigated, and valuable experience has been gained.



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CO<sub>2</sub> first appeared as a refrigerant in the middle of the 19<sup>th</sup> century. In the first half of the 20<sup>th</sup> century, CO<sub>2</sub> was replaced by the so-called safety refrigerants. As the ozone hypothesis first emerged in 1974, politicians reacted and adopted the Montreal Protocol in 1987. Since then, regulations and bans on synthetic refrigerants have been steadily increased. In the meantime, we arrived at the fourth generation of synthetic refrigerants, the so-called HFOs. These are currently being propagated by the chemical and refrigerant industry as a supposed solution, although their decomposition products can accumulate in surface water, are difficult to degrade and can thus also end up and cumulate in drinking water. It is to be expected that the HFO refrigerants, like their three previous generations, do not represent a long-term solution and the only future-proof refrigerants

are the natural ones. These are mainly carbon dioxide (CO<sub>2</sub>), ammonia (NH<sub>3</sub>) and the group of hydrocarbons (propane, etc.).

## Reversible heat pump

The commercial refrigeration system of the supermarket within the shopping mall is based on a CO<sub>2</sub> booster system with ejectors. The waste heat of the CO<sub>2</sub> booster system is used in priority for domestic hot water and facility heating. Any additional heating or air-conditioning demand is covered by the two reversible air-to-water CO<sub>2</sub> heat pumps. The reversible heat pumps are also equipped with ejectors to eventually achieve the highest possible efficiency. Table 1 shows the most important key figures of the reversible air-to-water heat pumps.

Table 1. Key figures of the air-to-water CO<sub>2</sub> heat pumps.

	Heating mode	Air-conditioning mode
Nominal capacity per heat pump (2x)	550 kW <sub>th</sub>	630 kW <sub>th</sub>
Ambient temperature	-8°C	+36°C
Temperature level	+30°C/+50°C	+12°C/+7°C
Gas cooler outlet temperature	+32°C	+38°C
High pressure	80 bar	95 bar
Evaporation pressure evaporator	-15°C	+5°C
Evaporating pressure compressor	-10°C	+10°C
Evaporator (2x)	3 x 125 kW <sub>th</sub> (air)	2 x 315 kW <sub>th</sub> (water)
Gas cooler (2x)	2 x 275 kW <sub>th</sub> (water)	3 x 285 kW <sub>th</sub> (air)
Compressor (2x)	6 pieces, 1 frequency converter (30 to 60 Hz)	
Ejectors (2x)	5 pieces, variable motive flow	
Piping lengths (between)	rack - gas cooler, one way: 75 m rack - heat/cold storage, one way: 150 m	
Heat/cold storage (each)	10 m <sup>3</sup> water	

Figure 1 shows the selected principle of the heat pumps, heating mode on the left, air-conditioning mode on the right. The pre-compression of the ejectors is visible in Figure 1. In heating mode, the CO<sub>2</sub> is pre-compressed from 23 bar to 27 bar. This corresponds to an evaporation temperature at the compressor of -10°C, which is above the air outlet temperature of -12°C. In air-conditioning

mode, the CO<sub>2</sub> is pre-compressed from 40 bar to 45 bar. This corresponds to an evaporation temperature at the compressor of +10°C, which is above the cold-water outlet temperature of +7°C. In the so-called “dual” operation mode, heating and air-conditioning can be provided simultaneously.

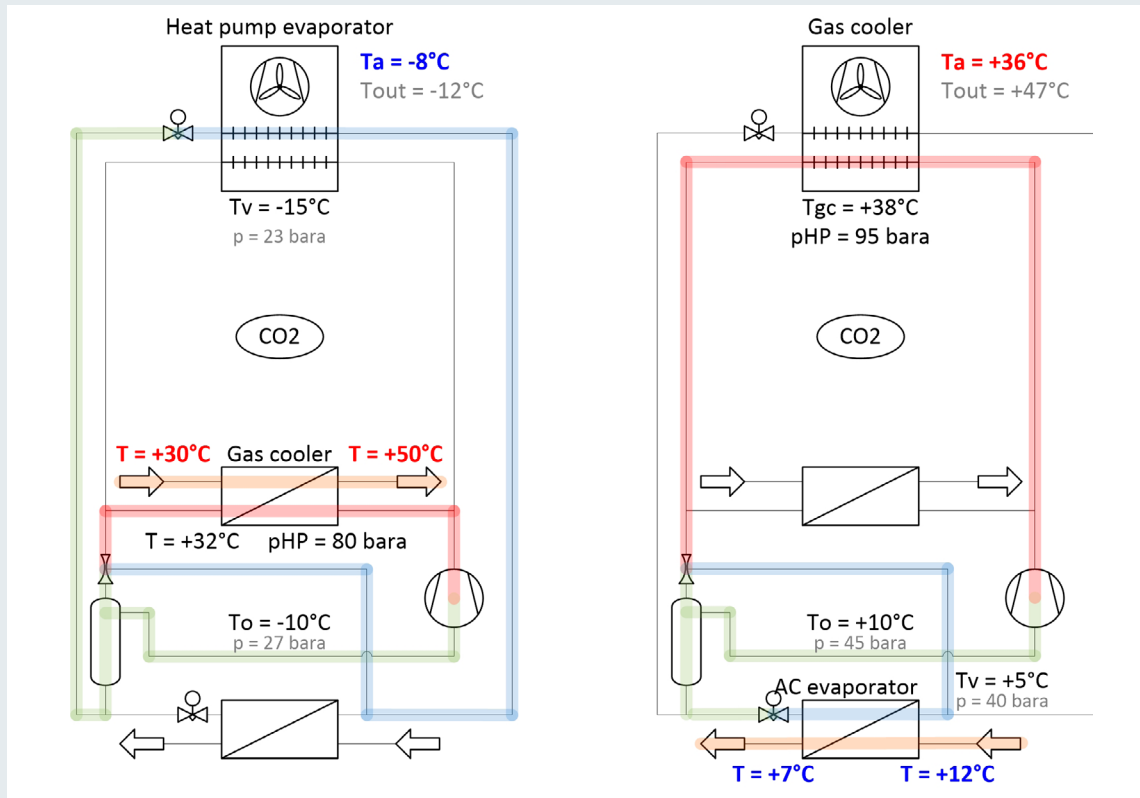


Figure 1. Schematic diagram of reversible air-to-water CO<sub>2</sub> heat pumps, left: heating mode, right: air-conditioning mode.

The heat pumps maintain the temperature level in the thermal storage for heating and air-conditioning. The frequency is controlled, and compressors are switched on and off to maintain the setpoint temperatures. The high pressure is controlled by the ejectors according to the optimum high-pressure setpoint, based on the gas cooler outlet temperature. The expansion valve controls the superheating of the evaporators. The evaporating pressure (evaporator), the medium pressure (evaporating pressure at compressor) and the resulting pressure lift of the ejectors adjust themselves, i.e., are not controlled. The water temperatures for heating and air conditioning are controlled on the waterside to the setpoint by the control valves. Figure 2 shows the project scope of the installed systems on-site.

### Operation Modes

At each point in time, each heat pump is assigned an independent, defined operating mode according to

Figure 3. If at least one (1) measurement value per time increment is missing, the point in time is assigned to the operating mode “Gap”. When a heat pump is not in operation, that point in time is assigned to the operation mode “Standby”. For the active operating modes, a distinction is made between “Chiller”, “Dual”, “Heat pump”, and “deFrost”. The operating modes “Heat pump” and “Chiller” are of particular interest for the evaluation and especially for the comparability with other systems. The “Dual” and “deFrost” operating modes depend strongly on further parameters so that a comparison with other systems is difficult.

### Operation Investigation

The following operational investigation is based on measurement data from the beginning of October 2020 to the end of September 2021. During the mentioned period, no fundamental changes on a component-level or control strategy of the system have been done. Accor-

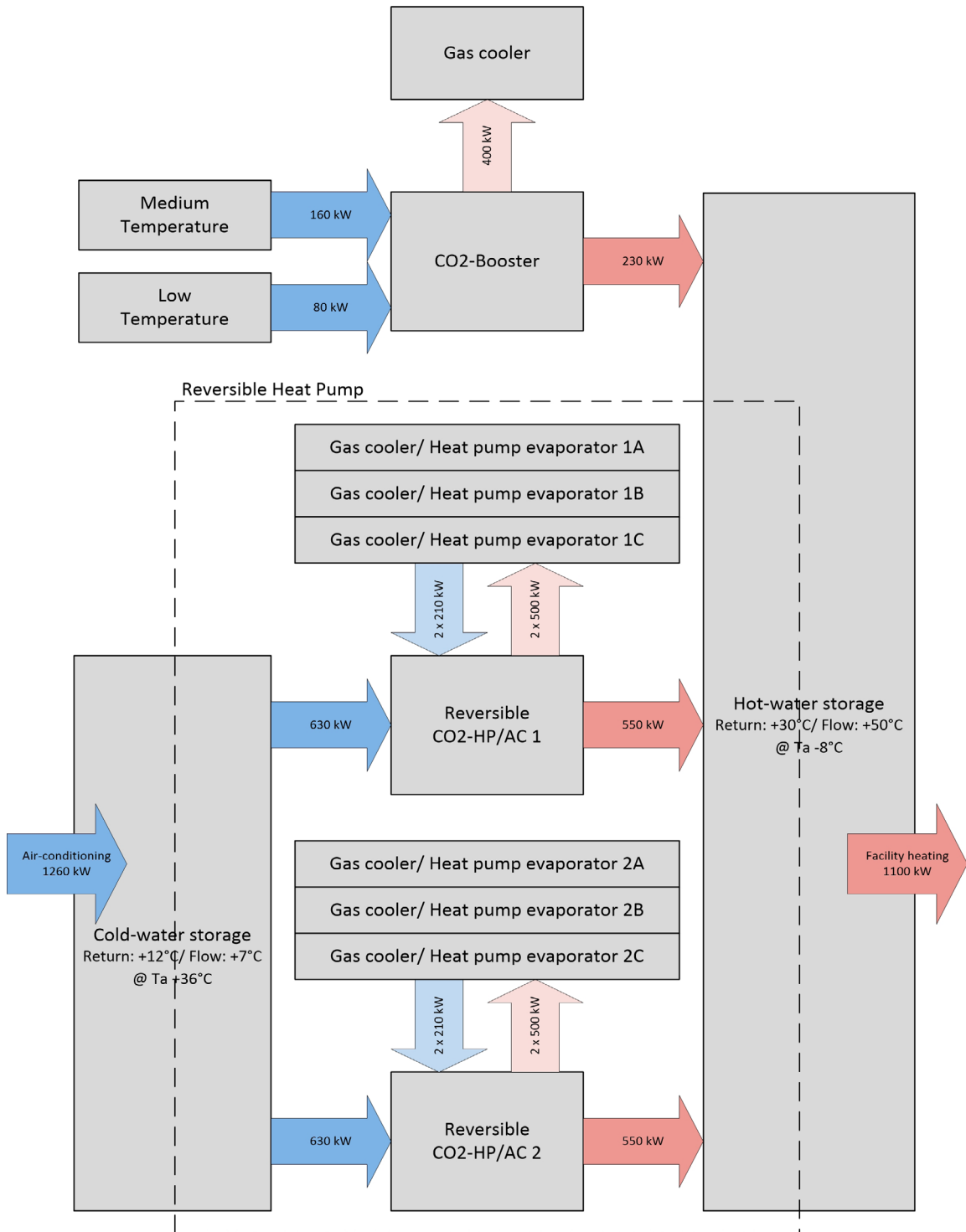
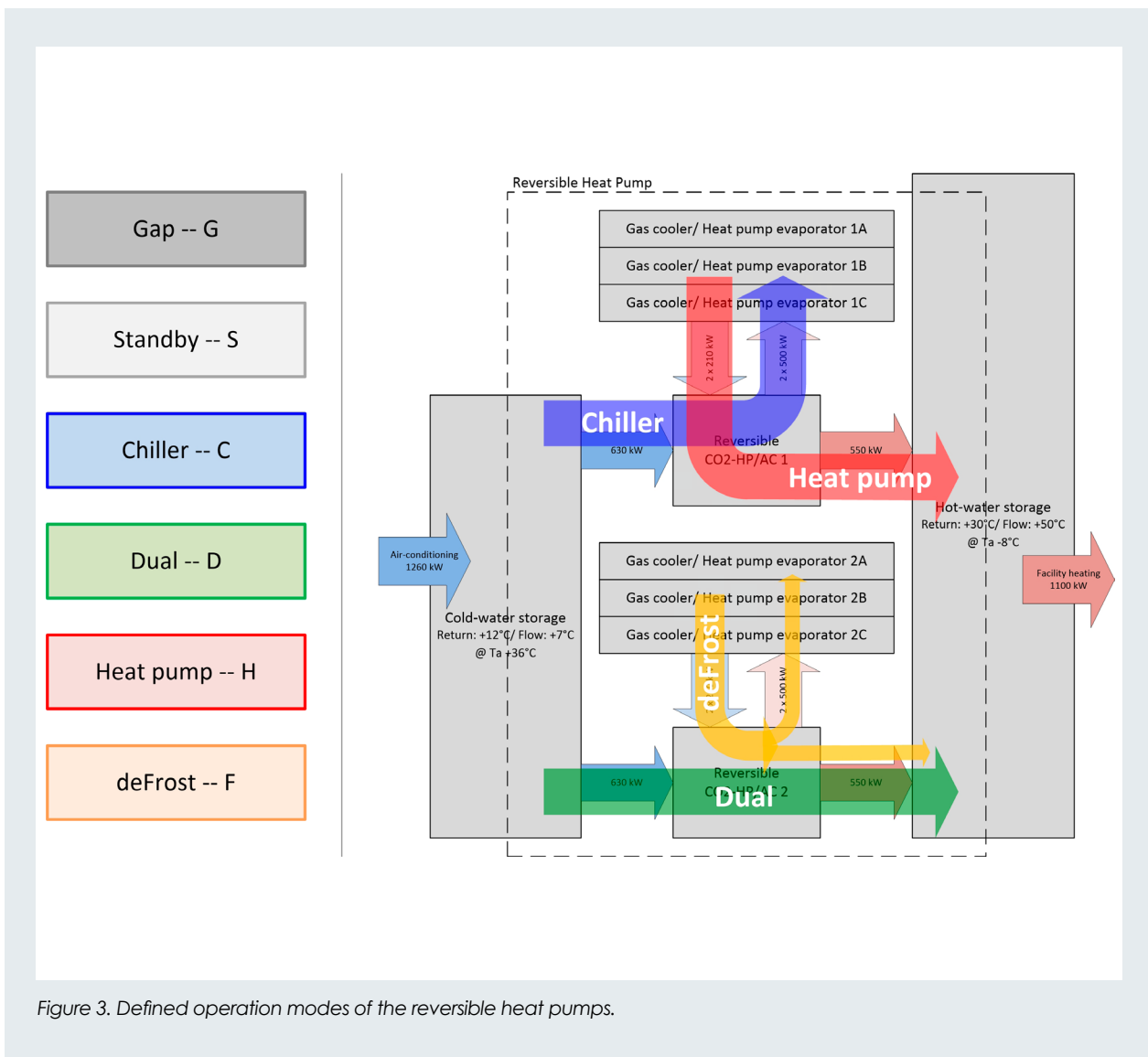


Figure 2. Overview of the CO<sub>2</sub> booster system and reversible CO<sub>2</sub> heat pumps installed on site.



ding to the Swiss federal office of meteorology and climatology, the winter of 2020/21 and the summer of 2021 were characterised by above-average rainfall amounts according to their climate bulletins. The mean temperature was above the long-term average. There was no extreme, prolonged cold in winter 2020/2021 and no extreme, prolonged heat in summer 2021. Due to the high rainfall amounts, the humidity in the environment was, in part, significantly higher.

### Heating

Figure 4 shows the average measured and predicted coefficient of performance (COP) during heating mode and the total provided heating energy of both heat pumps. The red, thick points correspond to the measured averaged values; the thin red line represents the predicted COP (model: operation). Weighted by the provided heating energy, the measured COP is -1.0% below the predicted COP over the entire temperature range. The annual performance factor of the heating mode is 3.33, without

considering the dual-mode (simultaneous heating and air-conditioning).

The measured COP is lower than the predicted COP in the upper-temperature range. According to current knowledge, the flattening and gradually decreasing COP in heating operation in the upper-temperature range can be attributed to partial load operation. This is very significant in heating mode, especially since several effects accumulate. Over the year (annual performance factor), however, this effect is limited, especially since the energy demand in this temperature range also decreases significantly.

In the lower temperature range, the measured COP is higher than the predicted COP. Based on current knowledge, this can be attributed to the lower return flow temperatures of the facility heating during operation. This effect can be modelled relatively easily and can be considered in future calculations. Furthermore, this

confirms the necessary rethinking for an efficient application of CO<sub>2</sub> heat pumps compared to conventional heat pumps. In contrast to conventional heat pumps, the efficiency of CO<sub>2</sub> heat pumps is not primarily determined by the forward flow temperature but by the return flow temperature and its temperature spread between flow and return temperature.

**Air-conditioning**

Figure 5 shows the average measured and predicted coefficient (COP) of performance in operation and the total provided air-conditioning energy of both heat pumps. The blue, thick points correspond to the mea-

sured averaged values; the blue, thin line represents the predicted COP (model: operation). Weighted according to the air-conditioning energy provided, the measured COP is -3.1% below the predicted COP over the entire temperature range. The annual performance factor in air-conditioning mode is 5.32 without considering the dual operation mode.

According to current knowledge, the lower COP in air-conditioning operation at lower ambient temperatures is mainly due to partial load operation and increased cycling of the heat pumps. Partial load operation becomes increasingly important in air-

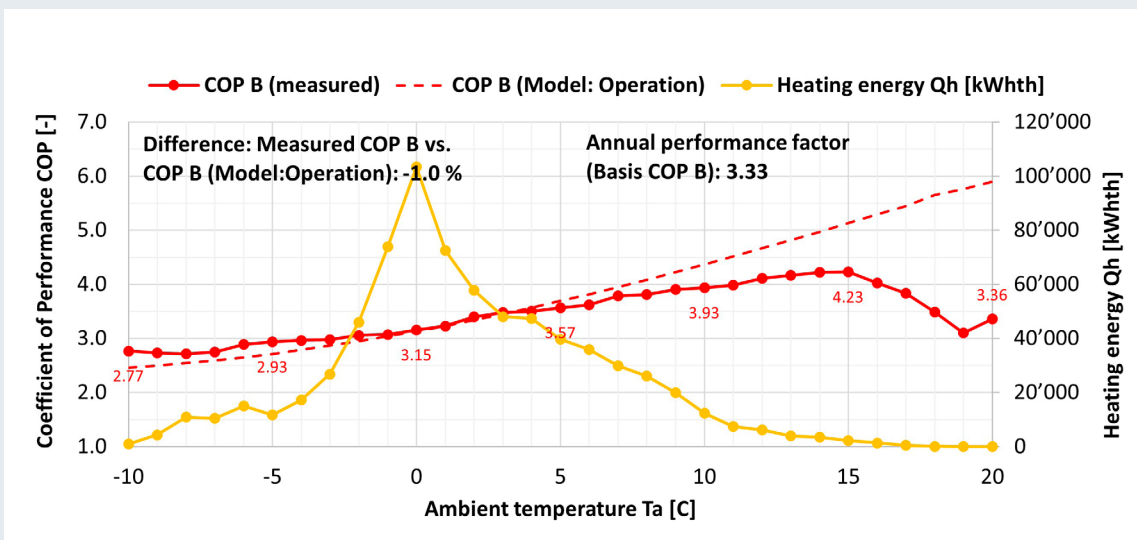


Figure 4. Average COP (heating mode) and total heating energy as a function of the ambient temperature of both heat pumps.

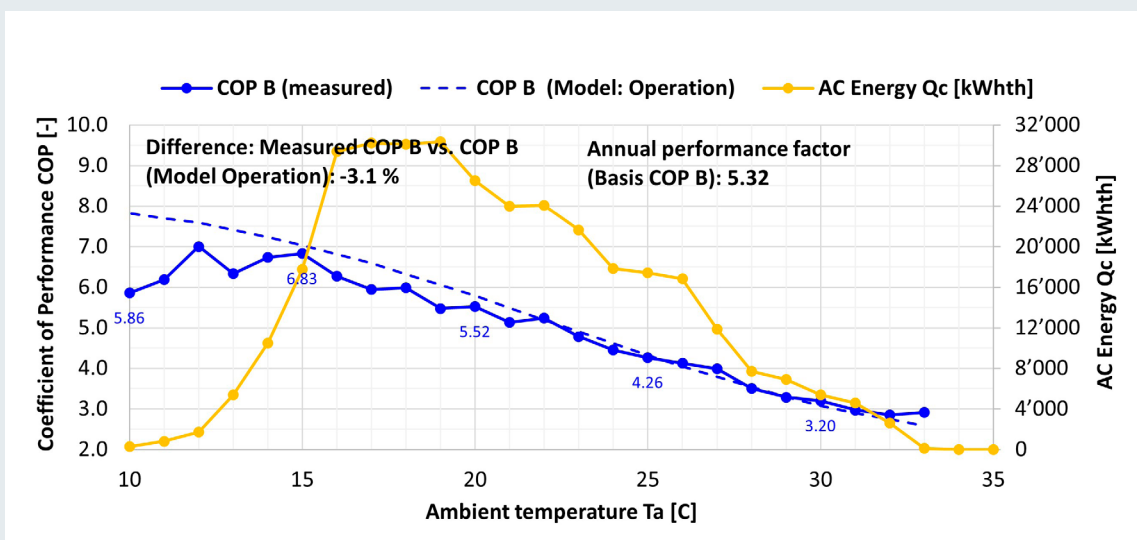


Figure 5. Average COP and total air-conditioning energy depending on the ambient temperature of both heat pumps.

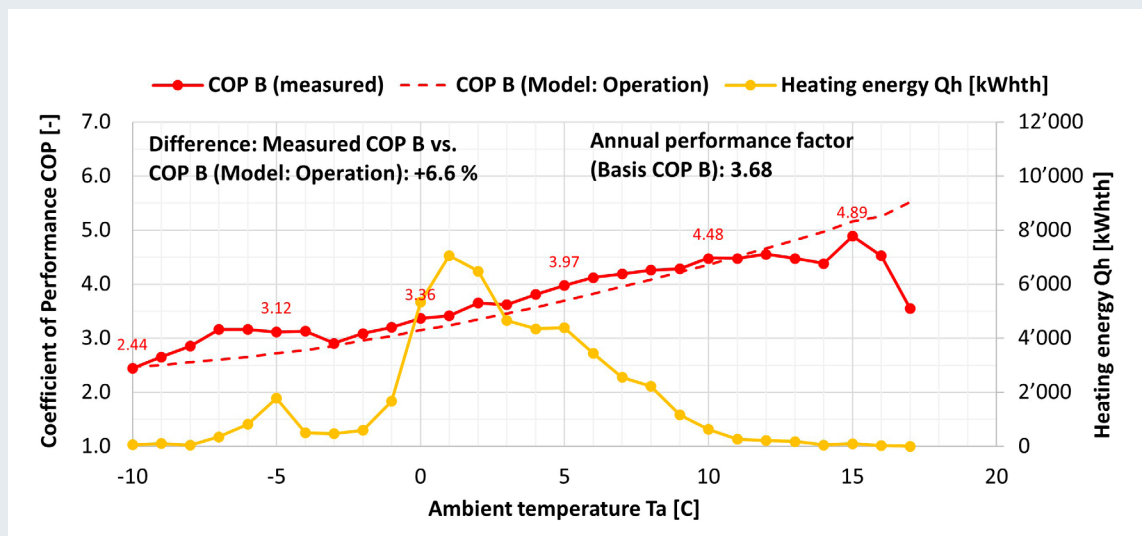


Figure 6. Average COP (heat pump) and total heating energy as a function of the ambient temperature of the heat pump installed at a follow-up Jobsite.

conditioning operation towards lower ambient temperatures, as it does in heating operation towards higher ambient temperatures. In addition, as the ambient temperature decreases, the high pressure (motive pressure) of the ejectors decreases and the suction effect of the ejectors decreases accordingly, which in turn makes stable process control noticeably more difficult. Over the year (annual performance factor), the measured COP values are 3.1% below the predicted values. In contrast to the heating mode, these points are more significant over the year, as the measured values are lower than the forecast in a relevant temperature range.

### Conclusions

In summary, the reversible air-to-water CO<sub>2</sub> heat pumps with ejectors have been operating successfully since autumn 2019. Valuable knowledge has been gained about their operating behaviour and the individual operating modes. In the meantime, a follow-up Jobsite based on the same CO<sub>2</sub> technology has already been successfully commissioned. The measured increase in efficiency at the mentioned follow-up Jobsite underline that relevant conclusion were drawn from the first Jobsite and that these were successfully incorporated.

Figure 6 shows the coefficient of performance (COP) of a follow-up Jobsite. The COP in heating mode could be increased from -1.0% to +6.6% compared to the model. The annual performance factor during heating mode of the follow-up Jobsite is 3.68 compared to the annual

performance factor of 3.33 in the first Jobsite. This comparison is without taking the dual operation into account.

The outlook to the follow-up Jobsite confirms that adjustments in the system design and operation result in an increase in the COP of around +8% compared to the model. It can be assumed that a further increase in efficiency can be achieved in further follow-up Jobsites. In addition to the energy optimisations, the system was simplified, and investment and operating costs were reduced. Considering the ecological concerns with synthetic refrigerants, as well as the fact that CO<sub>2</sub> is neither toxic nor flammable and, finally, the progress achieved in terms of efficiency, makes the authors confident that reversible air-to-water CO<sub>2</sub> heat pumps with ejectors will play a relevant role in future for heating and air-conditioning of modernised buildings.

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# United Kingdom: Strategic Market Outlook

Dr Matthew Aylott, Electrification of Heat Lead, UK Government

The publication of the UK Government’s Heat and Buildings Strategy in October 2021 and media interest in decarbonising heating, particularly in the year when Britain hosted the COP26 Climate Change Conference, has galvanised consumer interest in heat pumps. UK sales of hydronic heat pumps are forecast by industry to nearly double over the next year, and the UK is reaching a tipping point whereby heat pumps are being seen as a mainstream alternative to fossil fuel heating systems rather than a niche product.



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### UK heat pump market seeing rapid growth

Currently, there are around 300,000 hydronic heat pumps installed in the UK, largely monobloc air to water systems. This represents approximately 1 per cent of the UK heating market, which is dominated by gas boilers. Annual sales of heat pumps reached around 37,000 in 2020, but this was dwarfed by the annual sales of gas boilers which topped 1.7 million.

Despite the current market for heat pumps being relatively modest, there are big plans afoot. With the publication of the UK’s Heat and Buildings Strategy (Source: [BEIS](#)), the Government laid out an ambitious plan to grow the market to at least 600,000 installations a year by 2028. This plan will put the UK on a pathway that would mean around 1 in 6 homes will have a heat pump installed by the end of the decade, making the UK one of the largest markets in Europe for heat pumps (Figure 1).

Sector	Deployment assumptions	Unit	2019	2025	2030	2035	2050 illustrative range
Power	Electricity generation	TWh	320	315	370	460*-510	610-690
	Low carbon GB generation as a percentage of total projected generation required in 2035	%	29%-33%*	38%-42%*	62%-69%*	99%	99-100%
Heat and Buildings	Cumulative heat pumps installed domestically	Million installations	0.2	1.1	4*- 4.3	6.9* - 11.3	12-28
	Cumulative homes converted to 100% hydrogen for heat	Million homes	0	0	0-0.2*	0-4*	0-14
	Yearly homes treated by new domestic energy efficiency measures	Million homes	0	0.5	1	0.5	
	Low carbon fuels <sup>a</sup> consumption as a percentage of total fuel consumption in commercial buildings (excluding heat networks)	%	62%	63%	67%	78%-81%*	90-100%
	Yearly heat supplied via heat networks	TWh	14	16	22	29	70
	Yearly biomethane injected into the grid	TWh	3	8	12	12	0-20

Figure 1. Deployment assumptions underpinning UK Net Zero pathway (Source: [BEIS Net Zero Strategy, 2021](#))

### Building blocks for heat pump growth

To decarbonise buildings and support the switch to heat pumps, the Government will introduce requirements for new build homes that will mean – when the Future Homes Standard is implemented in 2025 – all new homes will need to be zero carbon ready; producing at least 75 per cent lower CO<sub>2</sub> emissions compared to those built to current standards. Subject to a full technical consultation in 2023, the intention is to set the performance standard of the Future Homes Standard at a level that will mean new homes will not be built with fossil fuel heating but with low carbon technologies, such as heat pumps, and will encompass very high fabric standards, and improved building services.

But to keep the UK on track to meet its carbon commitments and aid growth of supply chains also means taking action now; from later this year, there will be an interim uplift to building standards – so new homes will be expected to produce 31 per cent less CO<sub>2</sub> emissions compared to current standards; delivering homes that are future-proofed for the longer-term. Around 35% of heat pumps sold in the UK today are installed in new build, and this market is becoming increasingly important with many housing developers looking to fulfil their obligations under building regulations by deploying heat pumps, and indeed the Government expects a large majority of the 300,000 new homes to be built each year by the middle of the decade will have a heat pump installed. The UK Government are also taking action to move away from fossil fuel heating in existing homes and businesses by consulting on proposals to end the installation of new fossil fuel heating for homes and non-domestic buildings off the gas grid in this decade. This would start in 2024 for larger, non-domestic properties and from 2026 for households and smaller non-domestic buildings. The introduction of such regulation would effectively rule out the installation of new oil, coal or liquified petroleum gas heating systems once the appliance has reached the end of its life, and instead, consumers would be required to take a ‘heat pump first approach’, where a heat pump – or in limited cases biomass – would be installed in place of a fossil fuel heating system.

But Government analysis is clear that action is also needed in homes on the gas grid if the UK is to meet its net-zero objectives, and the Heat and Buildings Strategy outlined the intention to phase out the installation of new and replacement natural gas boilers by 2035 at the latest. There will continue to be gas boiler installations over the coming decade. These represent a significant target population for further improvements to in-home boiler performance, as well as measures to prepare homes for low carbon heating, such as sizing heat emitters for low-temperature operation. The government plan to consult shortly on whether to require new gas boilers to be hydrogen-ready from 2026 and also to test proposals on the future of broader boiler and heating system efficiency; this is in line with the timing of wider decisions on the future of the gas grid and the role of hydrogen.

### Bridging the cost gap

Introducing regulations is, of course, only part of the solution to growing the heat pump market in the UK. The average installed cost of an air source heat pump in the UK is around £10,500, which is around three times higher than incumbent heating technologies like gas boilers. When considered against the median UK household disposable income of £29,900 a year (Source: [ONS](#)), this represents a significant investment, and many consumers making the transition to low carbon heating currently rely on government support to help bridge the cost gap.

As part of the Heat and Buildings Strategy, the government announced funding of £3.9bn to help decarbonise buildings and kick start the market for heat pumps – including £450m for the new Boiler Upgrade Scheme, £950m for the Home Upgrade Grant, £800m for Social Housing, and £1.4bn for Public Sector Decarbonisation. But to make heat pumps more affordable and less reliant on government grants, costs must fall. This will be achieved naturally as the market grows and the supply chain becomes more competitive, but it is also likely to be driven by new financing models – like heat as a service – and applying process engineering approaches to streamline installation. The market is already responding by making significant commitments to reduce upfront costs, which could realise savings of 25-50% off the installed price of a heat pump by 2025.

The government has also been consulting on introducing a potentially game-changing market-based mechanism from 2024, with the leading option under consideration being to put an obligation on manufacturers of gas and oil boilers sold on the UK market to achieve the sale of a certain number of heat pumps proportional to their boiler sales in a given period. This approach has worked successfully in other industries and would put industry at the heart of the transition to cleaner heating, potentially driving rapid reductions in cost.

### Scaling up ambition requires fresh thinking

There are, of course, challenges facing the deployment of heat pumps in the UK. The UK remains reliant on gas boilers, with 85% of households connected to the national gas grid, and sales of gas boilers continue to grow, which has made re-training existing fossil fuel boiler engineers more challenging. But there are positive signs that existing installers are retraining and new installers are entering the market. There is also increasing interest and awareness of heat pumps among consumers.

And while it is true that many homes in the UK have radiators designed to operate at the high flow temperatures readily achieved by fossil fuel boilers, industry is responding by innovating and developing new technologies, like higher temperature heat pumps capable of working with the UK's existing heating systems. The UK Government is investing in developing such technologies through programmes like the £60 million Heat Pump Ready Innovation Programme.

There also remains much work to do to improve the fabric efficiency of the UK housing stock, to ensure that homes are insulated well enough to allow a heat pump to meet the thermal demands of consumers, but also to mitigate rising electricity costs that don't always allow consumers to make green decisions, because at present many consumers will see an increase in their fuel bills by switching to a heat pump. As part of the Heat and Buildings Strategy, Government announced plans to ensure that heat pumps are no more expensive to run than a gas boiler by incentivising insulation of homes and businesses, encouraging adoption of smart tariffs, promoting improved efficiency of products and considering approaches to remove price distortions in the levies applied to gas and electricity prices.

While challenges exist in reaching the Government's ambitious deployment targets for heat pumps, there is cause for optimism and a genuine sense that the UK has reached a tipping point in its approach to decarbonising heat.

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INFORMATION

## Become a subscriber

### The Heat Pumping Technologies Magazine

Three times a year, the Heat Pump Center issues the Heat Pumping Technologies Magazine.

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## Events 2022 – 2023

Please check for updates for any conference that you plan to attend. Venues and dates may change, due to the pandemic.

**21–23 March**  
**ACEEE Hot Water Forum**

Atlanta, USA

<https://www.aceee.org/2022-hot-water-forum>

**7–8 April**  
**European Energy Efficiency Conference 2022**

Wels, Austria

<https://mailchi.mp/eceee/wsed2022-sent06-october-827382?e=9a30a52a3a>

**8–10 April**  
**The 10<sup>th</sup> Asian Conference on Refrigeration and Air-Conditioning (ACRA 2022)**

Chongqing, China

<https://acra2022.scimeeting.cn/en/web/index/>

**11–13 April**  
**7<sup>th</sup> IIR Conference on Sustainability and the Cold Chain**

Newcastle, United Kingdom

<https://ior.org.uk/the-7th-iir-conference-on-sustainability-and-the>

**4–6 May**

(postponed from 13–15 September, 2021)

**IAQ 2020: Indoor Environmental Quality Performance Approaches - Transitioning from IAQ to IEQ**

Athens, Greece

<https://www.ashrae.org/conferences/topical-conferences/indoor-environmental-quality-performance-approaches>

**10–12 May**  
**HPT TCP Executive Committee meeting (Only for delegates, operating agents, and invited guests)**

Oslo, Norway

**11–12 May**  
**Decarb Cities 2022**

Vienna, Austria

<https://decarbcities.eu/>

**22–25 May**  
**CLIMA 2022**

Rotterdam, The Netherlands

<https://clima2022.org/>

**6–10 June**  
**eceee in-person 2022 Summer Study**

Hyères, France

<https://www.eceee.org/all-news/news/eceee-announces-in-person-summer-study-in-june-2022/>

**13–15 June**  
**15<sup>th</sup> IIR-Gustav Lorentzen Conference on Working Fluids**

Trondheim, Norway

[https://www.sintef.no/projectweb/gustavlorentzen\\_2022/](https://www.sintef.no/projectweb/gustavlorentzen_2022/)

**25–29 June**  
**2022 ASHRAE ANNUAL CONFERENCE**

Toronto, Canada

<https://www.ashrae.org/conferences/2022-annual-conference-toronto>

**10–14 July**  
**Purdue: International Compressor Engineering, International Refrigeration & Air-Conditioning**

W. Lafayette, Indiana, USA

<https://engineering.purdue.edu/Herrick/about/news/Conferences/2022>

**10–12 Nov**  
**HPT TCP Executive Committee meeting (Only for delegates, operating agents, and invited guests)**

United Kingdom

**11–13 November**  
**Chillventa**

Nürnberg, Germany

<https://www.chillventa.de/en>

## 2023

**15–18 May**  
**The 14th IEA Heat Pump Conference in Chicago (HPC2023)**

Chicago, Illinois, USA

<https://www.hpc2023.org/>

**IN THE NEXT ISSUE**  
**Control and Monitoring of Heat Pump Systems**

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### International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organization for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among its participating countries, to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development.

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

International collaboration for energy efficient heating, refrigeration, and air-conditioning.

### Vision

Heat pumping technologies play a vital role in achieving the ambitions for a secure, affordable, high-efficiency and low-carbon energy system for heating, cooling and refrigeration across multiple applications and contexts.

The Programme is a key worldwide player in this process by communicating and generating independent information, expertise and knowledge related to this technology as well as enhancing international collaboration.

### Mission

To accelerate the transformation to an efficient, renewable, clean and secure energy sector in our member countries

and beyond by performing collaborative research, demonstration and data collection and enabling innovations and deployment within the area of heat pumping technologies.

### Heat Pump Centre

A central role within the HPT TCP is played by the Heat Pump Centre (HPC). The HPC contributes to the general aim of the HPT TCP, through information exchange and promotion. In the member countries, activities are coordinated by National Teams. For further information on HPC products and activities, or for general enquiries on heat pumps and the HPT TCP, contact your National Team at [www.heatpumpingtechnologies.org/contact-us/](http://www.heatpumpingtechnologies.org/contact-us/)

The Heat Pump Centre is operated by RISE Research Institutes of Sweden.



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